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# JOURNAL OF THE AMERICAN ROCKET SOCIETY

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ROBERTSON YOUNGQUIST, Editor

The JOURNAL OF THE AMERICAN ROCKET SOCIETY is devoted to disseminating information on the development of rocket and jet propulsion by printing original technical papers on jet propulsion, data on the latest experimental developments, historical notes, patent specifications, reviews of books and current literature, and news of the Society and individual members.

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# ROCKET POWER PLANTS

## LIQUID-PROPELLANT ROCKET POWER PLANTS

The ATO power plant pictured here in operation on the B-45 is one of many Aerojet liquid-propellant rocket developments.

## SOLID-PROPELLANT ROCKET MOTORS

The certification by CAA for commercial use of the Aerojet JATO 14AS-1000D5 motor is a significant step forward for rocketry. A new JATO—lighter by nearly 50% and operable over a considerably wider temperature range—has been successfully tested.

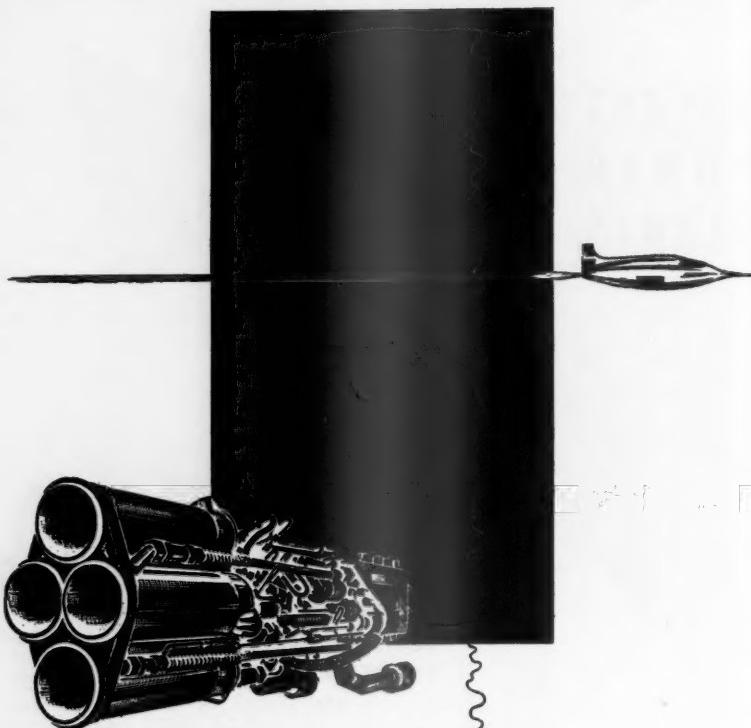
## THE AEROBEE

Aerojet's Aerobee sounding rocket (liquid sustaining motor, solid booster), in probing Earth's upper atmosphere at altitudes of 50 to 75 miles—at the geomagnetic equator off the coast of Peru, over the Gulf of Alaska, over a point off the Washington coast, and over New Mexico, has proved to be the most effective and economical rocket of its type yet developed.

The Aerojet logo consists of the word "Aerojet" written in a stylized, italicized script font, with a horizontal line extending from the left side of the "A".

ENGINEERING CORPORATION  
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SUBSIDIARY OF THE GENERAL TIRE AND RUBBER CO.



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# JOURNAL OF THE AMERICAN ROCKET SOCIETY

Number 80

ROBERTSON YOUNGQUIST, *Editor*

March, 1950

## HYDROGEN PEROXIDE AS A PROPELLANT

By Ralph Bloom, Jr., Noah S. Davis, Jr., and  
Samuel D. Levine

Production Supervisors, Special Projects Department, Buffalo Electro-Chemical Company, Inc., Buffalo, N. Y.

### Introduction

Concentrated hydrogen peroxide ( $H_2O_2$ ) is one of the leading liquid rocket propellants. The Germans successfully used somewhat impure solutions of 80 to 85 per cent  $H_2O_2$  by weight as oxidizers in rocket motors and for steam generation in turbine pump drives, launching ramps, and the like. The present availability of pure, stable, 90 per cent  $H_2O_2$  and the expanding knowledge of, and experience with, its handling and storage characteristics make concentrated  $H_2O_2$  very attractive for rocket and guided-missile development.

This material requires only a few simple precautions for safe handling either in bulk or in small lots. It is a liquid which is stable in extended storage over a wide range of normal temperatures; it has high density, negative heat of formation, high specific energy release, and a high percentage of available oxygen. It will form spontaneous igniting mixtures with fuels. Finally, 90 per cent  $H_2O_2$  has for some time been readily available in commercial quantities.

The present and potential availability of 90 per cent  $H_2O_2$  can best be illustrated by the development of production facilities by the Buffalo Electro-Chemical Company, Inc. At the request of the Chemical Warfare Service, at the height of the war, in 1944, BECCO designed, constructed, and operated within a period of seven weeks a dependable pilot plant capable of producing 90 per cent  $H_2O_2$  by weight. Improvements in safety, dependability, and efficiency followed the first successful production. In 1946 when the commercial production of bleaching peroxide was expanded and modernized, a commercial production unit for 90 per cent  $H_2O_2$  was included. This unit can be readily reproduced in a short period of time when the demand warrants it. Expansion in 90 per cent  $H_2O_2$  production facilities is based upon expanded production of 30 to 35 per cent  $H_2O_2$ .

Presented at the 1949 Annual Convention of the AMERICAN ROCKET SOCIETY, Hotel Statler, New York, N. Y., Nov. 28-Dec. 2, 1949.

Therefore, it is directly dependent upon the available electric power which is the principal raw material used for H<sub>2</sub>O<sub>2</sub> production.

The latest information on the properties of 90 per cent H<sub>2</sub>O<sub>2</sub> which are pertinent to the rocket engineer are summarized herein. Handling and storage characteristics are described, and compared with those of other liquid oxidizers. Finally, its potential as an oxidizer in combination with carbon- or nitrogen-bearing fuels and as a monofuel are outlined and critically discussed.

Although much information on the properties and use of concentrated H<sub>2</sub>O<sub>2</sub> has been published, the extensive development studies and the experience amassed in the last several years warrant recapitulation.

### Description of 90 Per cent H<sub>2</sub>O<sub>2</sub>

*Physical Properties:* The more important physical properties of H<sub>2</sub>O<sub>2</sub>, 90 per cent by weight in aqueous solution, are summarized in Table 1. It is a clear liquid similar in appearance and viscosity to fresh water. Normally, it is supersaturated with oxygen, and upon agitation releases this with more or less effervescence. Tests have shown that after 16 hours at approximately 800 psi and room temperature, sudden release to atmospheric pressure produces gas bubbles but no foaming or excessive increase in volume. Furthermore, this supergaseous saturation does not create excessive cavitation or vapor binding at the suction of low-pressure centrifugal transfer pumps.

TABLE 1. PHYSICAL PROPERTIES OF 90 PER CENT H<sub>2</sub>O<sub>2</sub>

Density at 68 F.....	1.39 gm/cc 11.62 lb/gal
Viscosity at 64.4 F.....	1.30 centipoises
Vapor pressure at 86 F.....	5 mm
Heat of formation, liquid.....	45.16 kcal/gmol
(100% H <sub>2</sub> O <sub>2</sub> ) vapor.....	33.29 kcal/gmol
Freezing point ( <i>Note:</i> When frozen solid contracts by 11% of liquid volume).....	12 F
Normal boiling point.....	284 F
Heat of vaporization.....	590 Btu/lb
Heat capacity, 0-18.5 C.....	0.58 cal/gm C
Surface tension at 64.4 F.....	75.53 dynes/cm
Dielectric constant at 68 F.....	77
Conductivity, pure, at 77 F.....	2 × 10 <sup>-8</sup> /ohm cm
Conductivity, commercial, at 77 F.....	10 × 10 <sup>-8</sup> /ohm cm
Refractive index at 68 F.....	1.398
Nonvolatile residue (commercial, specified), ppm.....	50
Nonvolatile residue (actual), ppm.....	20
Stability, commercial.....	No loss in storage at 122 F (50 C)

Source: "Hydrogen Peroxide—Physical Properties," Becco Data Book 1949.

Since density, vapor pressure, and freezing points are of special interest, curves of these data are presented for 70 per cent  $\text{H}_2\text{O}_2$  solutions in Figs. 1, 2, and 3.

Although concentrated  $\text{H}_2\text{O}_2$  solutions have freezing points above zero Fahrenheit, the liquid-solid phase diagram for the  $\text{H}_2\text{O}_2$ - $\text{H}_2\text{O}$  system indicates that for higher concentrations the solid phase is more concentrated than the liquid phase with which it is in equilibrium. Therefore, until the eutectic temperature of -67 F is reached, it will form only a slush of heavy crystals in a lower concentration of liquid. In addition, there is a decided supercooling effect. For example, pure stable 90 per cent  $\text{H}_2\text{O}_2$  will regularly supercool in a glass tube to -60 F even when agitated, or when strips or particles of stainless steel, aluminum, or plastics have been added. Slight decomposition diminishes the supercooling effect. Although the crystallization cannot apparently be seeded by surface imperfections of the vessel walls, both

$\text{H}_2\text{O}_2$  and ice crystals will readily cause freezing when the liquid is in the supercooled state.

Addition of ammonium nitrate ( $\text{NH}_4\text{NO}_3$ ) to 90 per cent  $\text{H}_2\text{O}_2$  will produce lower freezing point mixtures as shown in Fig. 4. For the optimum mixture, 40 per cent  $\text{NH}_4\text{NO}_3$  and 60 per cent  $\text{H}_2\text{O}_2$ , the calculated theoretical specific energy available is at least equal to that available from the 90 per cent alone.

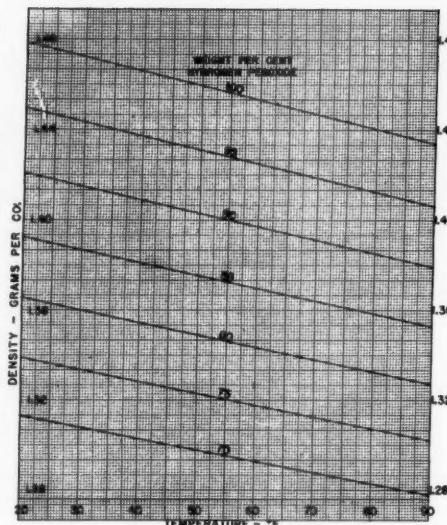


FIG. 1 DENSITY OF 70-100%  $\text{H}_2\text{O}_2$  SOLUTIONS OVER THE RANGE 20-90 F

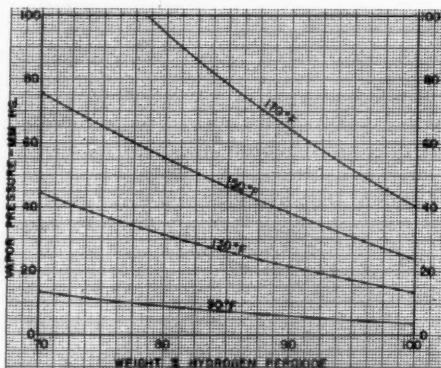


FIG. 2 VAPOR PRESSURE OF  $\text{H}_2\text{O}_2$ - $\text{H}_2\text{O}$  SYSTEM, 90-170 F, 70-100%  $\text{H}_2\text{O}_2$

Therefore, it is directly dependent upon the available electric power which is the principal raw material used for H<sub>2</sub>O<sub>2</sub> production.

The latest information on the properties of 90 per cent H<sub>2</sub>O<sub>2</sub> which are pertinent to the rocket engineer are summarized herein. Handling and storage characteristics are described, and compared with those of other liquid oxidizers. Finally, its potential as an oxidizer in combination with carbon- or nitrogen-bearing fuels and as a monofuel are outlined and critically discussed.

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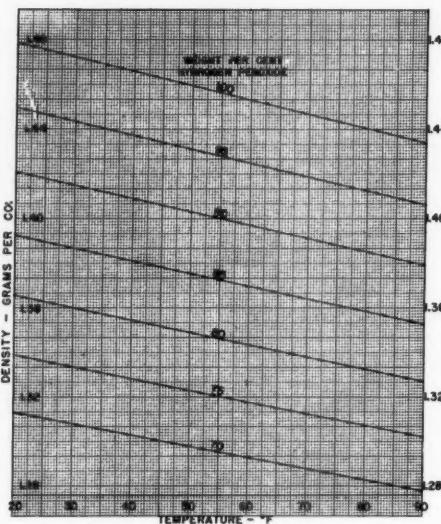


FIG. 1 DENSITY OF 70-100%  $H_2O_2$  SOLUTIONS OVER THE RANGE 20-90 F

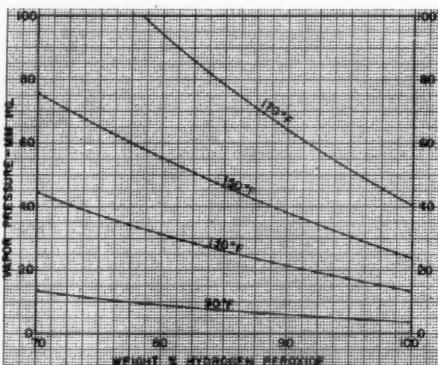
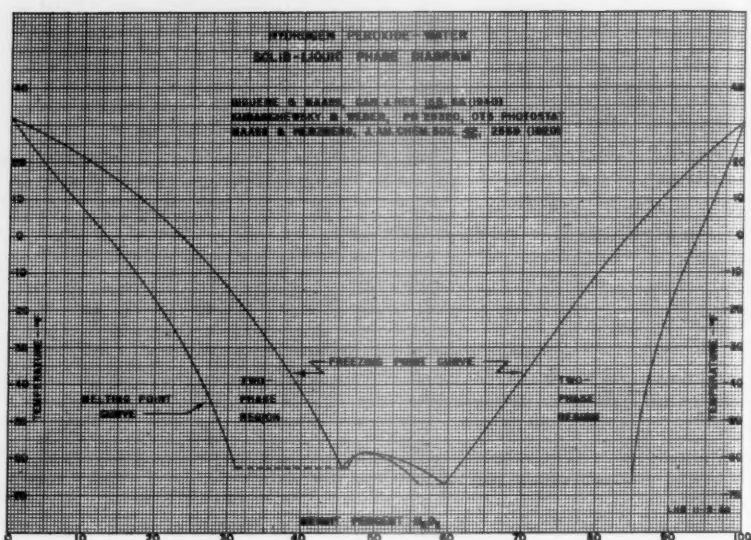


FIG. 2 VAPOR PRESSURE OF  $H_2O_2$ - $H_2O$  SYSTEM, 90-170 F, 70-100%  $H_2O_2$

FIG. 3 LIQUID-SOLID PHASE DIAGRAM,  $\text{H}_2\text{O}_2\text{-H}_2\text{O}$ 

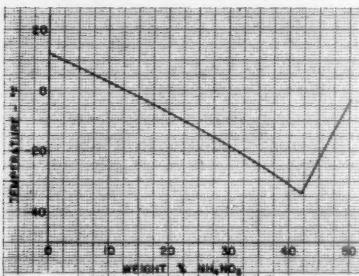
**Decomposition Characteristics:** Concentrated  $\text{H}_2\text{O}_2$  is readily and efficiently decomposed by many common catalysts or by heat. Nascent or active oxygen is released and water is the inactive by-product. In addition, it has strong oxidizing action, as one pound of decomposed 90 per cent  $\text{H}_2\text{O}_2$  releases 0.423 lb of active oxygen.

Details on the catalytic decomposition of concentrated  $\text{H}_2\text{O}_2$  have been covered in previous publications. The permanganates, which were the standby of German practice, are common chemical examples in oxidation-reduction reactions. The Germans also used copper ions in the form of

$\text{KCu}(\text{CN})_6$  pills for starting catalysts in the Messerschmitt Me-163B rocket motor.

Combustion of hydrocarbon fuels is readily attained with  $\text{H}_2\text{O}_2$  and a proper liquid catalyst. A spontaneous igniting mixture is formed with anhydrous hydrazine.

**Energy Properties:** Concentrated  $\text{H}_2\text{O}_2$  decomposes with the evolution of heat and large quantities of a gas mixture of oxygen and superheated steam. Fig. 5 presents the

FIG. 4 FREEZING POINT OF 90%  $\text{H}_2\text{O}_2\text{-NH}_4\text{NO}_2$  MIXTURES

data on the heat of decomposition, the adiabatic decomposition temperatures, and the volume of gas released for the 67 to 100 per cent  $H_2O_2$  solutions. One pound of 90 per cent  $H_2O_2$  at a reference temperature of 32 F evolves 1110 Btu, and 60 cu ft of gas at 1364 F. Data on the decomposition products of 90 per cent  $H_2O_2$  are listed in Table 2.

*Storage and Handling:* For several years, 90 per cent  $H_2O_2$  has been shipped in ICC-approved pure aluminum drums, containing 250 lb of liquid. These are vented by means of simple Bunsen valves with Koroseal diaphragms which release at 3 psig, Fig. 6. Use of a double head and elimination of the standard side bung prevents spillage of the  $H_2O_2$ . The recommended means of emptying is an aluminum siphon which is also shown.

Storage in these and similar pure aluminum drums is very satisfactory. Ten drums of 90 per cent  $H_2O_2$ , manufactured and shipped in May, 1945,

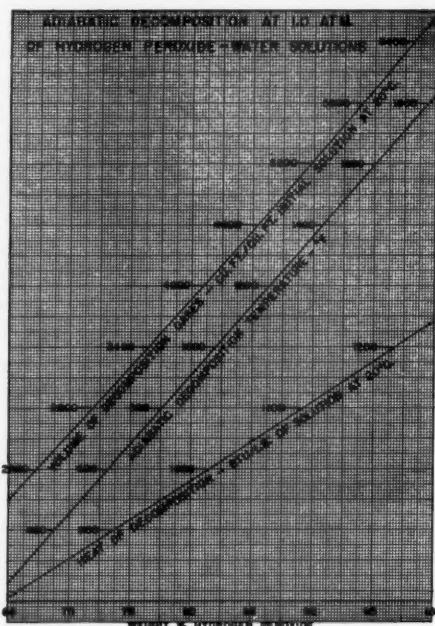


FIG. 5 DECOMPOSITION OF 65-100%  $H_2O_2$  SOLUTIONS

TABLE 2 PROPERTIES OF DECOMPOSITION PRODUCTS OF 90 PER CENT  $H_2O_2$

Unconfined System at 1.0 Atm

Enthalpy.....	1110 Btu/lb sol
Entropy.....	2.65 Btu/lb R
Temperature.....	1364 F
Volume.....	60 cu ft/lb sol
Heat capacity	
constant pressure.....	0.43 Btu/lb F
constant volume.....	0.34 Btu/lb
Ratio, $k$ .....	1.266
Average molecular weight.....	22.1
Mole fraction, $O_2$ .....	0.2924
Mole fraction, $H_2O$ .....	0.7076
Weight per cent, $O_2$ .....	42.3
Weight per cent, $H_2O$ .....	57.7

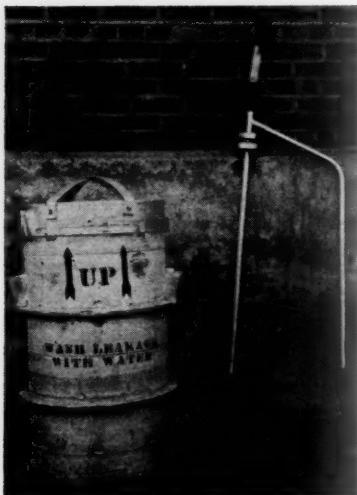
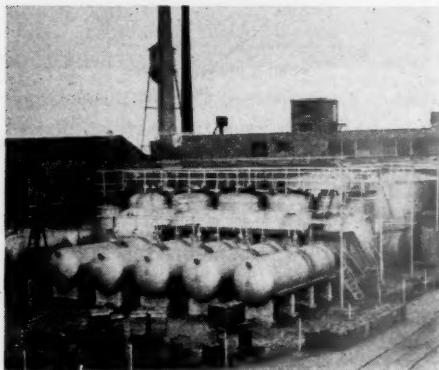
FIG. 6 90% H<sub>2</sub>O<sub>2</sub> DRUM AND SYPHON

FIG. 7 BULK STORAGE TANKS



FIG. 8 TANK CARS

showed in October, 1948, an average concentration loss of 0.9 per cent per year after handling by several Army depots and an accumulated shipping mileage of perhaps 6000 miles. This H<sub>2</sub>O<sub>2</sub> was pilot-plant product and apparently no special attention was paid to cleanliness in storage.

Drums of 90 per cent H<sub>2</sub>O<sub>2</sub> are generally handled on wooden pallets by lift trucks or dollies. They are never rolled or laid on their sides. Shipments are made both by rail and truck. Specified precautions are ICC-white label, designating the contents as corrosive, if spilled.

Bulk lots of 90 per cent H<sub>2</sub>O<sub>2</sub> have been stored in large vented pure aluminum tanks up to 30,000-gal capacity, Fig. 7. These have no openings below the liquid level. A liquid volume of 90 per cent of the tank interior volume is generally considered maximum filling. Bulk shipments of 90 per cent H<sub>2</sub>O<sub>2</sub> are made in 4000-gal capacity pure aluminum tank cars, Fig. 8. These cars are completely filled to the dome for shipment. A dip pipe from the suction side of a pump is used to empty these cars. All tanks either portable or stationary are vented by means of a porous filter stone and a Bunsen valve.

Investigations have been pursued to adapt commercially available equipment to 90 per cent H<sub>2</sub>O<sub>2</sub> transfer systems. Recent expansion in the fabrication of stock pumps,

TABLE 3 REPRESENTATIVE SOURCES OF SUPPLY OF H<sub>2</sub>O<sub>2</sub> HANDLING EQUIPMENT

Item No.	Equipment	Materials	Supplier	Address
1	Small transfer pump, 10 gpm	Aluminum 43	Portable Pump Co.	St. Louis, Mo.
2 (a)	Transfer pumps, 35 gpm	Aluminum 43 or 316 steel	LaBour Pump Co.	Elkhart, Ind.
(b)	.....	Durimet 20 and Teflon seal	The Duriron Co.	Dayton, Ohio
3 (a)	Valves, globe	300 series stainless steel and Teflon disk	Alloy Steel Prod. Co.	Linden, N. J.
(b)	Valves, gate	Aluminum 43	Wm. Powell Co.	Cincinnati, Ohio
(c)	Valves, quick-opening	300 series stainless steel	Crane Co.	Chicago, Ill.
(d)	Valves, needle high pressure	300 series stainless steel and Teflon	Reading, Pratt & Bridgeport, Cady Valve Div., Conn. Alloy Steel Prod. Co.	Linden, N. J.
(e)	Valves, check	300 series stainless steel and Teflon	Jet Specialties Co.	Los Angeles, Calif.
(f)	Valves, wye	300 series stainless steel and Teflon	Kohler Co.	Kohler, Wis.
(g)	Valves, plug	300 series stainless steel	Hasco Valve & Machine Co.	Milwaukee, Wis.
			Nordstrom Valve Div., Rockwell Mfg. Co.	Pittsburgh, Pa.
4 (a)	Hose, flexible	Polyethylene lined, stainless steel armored	Jet Specialties Co.	Los Angeles, Calif.
(b)	.....	347 stainless steel bellows and armor	Eclipse Pioneer Div., Bendix Aviation Corp.	Teterboro, N. J.
5 (a)	Meters, flow	300 series stainless steel	Fischer & Porter Co.	Hatboro, Pa.
(b)	.....	300 series stainless steel	Brooks Rotameter Co.	Lansdale, Pa.
(c)	.....	300 series stainless steel	Schutte & Koerting Co.	Philadelphia, Pa.
6 (a)	Gauges	300 series stainless steel	Johnston Engineering Co.	Rochester, N. Y.
(b)	.....	300 series stainless steel	Clapp Instrument Co.	Providence, R. I.
7 (a)	Strainers	300 series stainless steel basket	Leslie Co.	Lindhurst, N. J.
(b)	.....	Porous stone (99.6% SiO <sub>2</sub> )	Filtros Corp.	East Rochester, N. Y.
8 (a)	Packings	Teflon ring	U. S. Gasket Co.	Camden, N. J.
(b)	.....	Braided Teflon and Teflon ring	Crane Packing Co.	Chicago, Ill.
(c)	.....	Glass fiber plaited, grease-free	Marlo Co., Inc.	New York, N. Y.

valves, piping, gasketing, and other transfer equipment from AISI Series 300 stainless steels, aluminum alloys, and plastics such as polyethylene and teflon allows a reasonable selection from catalogs for  $H_2O_2$  service.

Table 3 lists the sources of commercial items of equipment which have been tested and found suitable for 90 per cent  $H_2O_2$  transfer. Every article installed in a 90 per cent  $H_2O_2$  transfer system must first be thoroughly cleaned and passivated. In addition, the systems should be installed to drain and vent completely. Decomposition of trapped  $H_2O_2$  will always occur and excessive pressure build-up may result if venting is not provided.

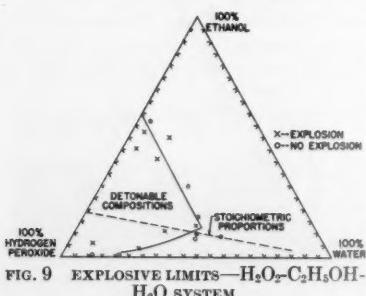
### Safety Precautions

**Fire Hazard:** Tests have indicated that 90 per cent  $H_2O_2$  in contact with clean textiles and woods will not cause fire. However, if these materials are contaminated with catalysts such as rust, concrete, and dust, spontaneous ignition and extremely hot flame will result. Water is the protective medium to use and should be available in large quantities in any area of  $H_2O_2$  transfer.

Spillage on clothing is especially dangerous because of combustion delay. Once a fire is generated, it is extremely hot and can cause serious burns. Safety showers should be provided in transfer areas. Workmen should wear protective clothing and always work in pairs.

**Explosion Hazard:** Ninety per cent  $H_2O_2$  has been subjected to numerous detonation tests. Bellinger, et al, established that 90 per cent  $H_2O_2$  is not shock sensitive to a hammer blow of 70 kg cm; to a gas hammer pressure of 2000 psi; or to 0.50 caliber, armor-piercing and incendiary bullets at 100 yd. Tests carried out at BECCO and reported by Messrs. Shanley and Greenspan have shown that 90 per cent  $H_2O_2$  will not propagate detonation if subjected to mechanical impact from a drop weight tester; to rifle and pistol fire; or by blasting caps with and without booster charges.

Even under confinement and severe conditions of shock, uncontaminated 90 per cent  $H_2O_2$  at ambient temperatures cannot be detonated. If it is heated sufficiently to produce concentrations of vapor, the danger of extremely rapid decomposition exists. Such decomposition may shatter a length of stainless steel tubing, bursting pressure 10,000 psi, but there will not be propagation in the liquid stream. Although 90 per cent  $H_2O_2$  is not sensitive



to shock alone, the combination of heat and shock may be dangerous. The exact conditions are not known, but the temperature of the liquid must exceed the boiling point, and concentrated vapor must be present.

Certain mixtures of 90 per cent  $H_2O_2$  with organic liquids and wetted solids form high explosives. An example of the range of mixtures which are explosive is presented in Fig. 9 for the peroxide-alcohol-water system. The sensitivity of mixtures of 90 per cent  $H_2O_2$  and fuels cannot be overstressed. If accidental mixing occurs, the mixture should be immediately diluted with copious quantities of clean water.

Another danger to be considered is contamination in storage. Though normal venting is provided, if liquid decomposition is initiated the rate of gas evolution will increase exponentially until it may exceed the venting capacity. If  $H_2O_2$  in a container begins to heat internally due to exothermic decomposition, steps should immediately be taken to retard this condition. Addition of 8 to 10 ppm of phosphoric acid may slow the action; if not, fresh water dilution to 67 per cent  $H_2O_2$  or below will completely eliminate any danger.

**Toxicity:** Concentrated  $H_2O_2$  and  $H_2O_2$  vapors are irritants, but are not toxic. Tests at Huntsville Arsenal in the early period of 90 per cent  $H_2O_2$  production indicated that its contact with the skin caused stinging and bleaching;  $H_2O_2$  vapor will irritate the eyes, but has no permanent effect. Washing with water immediately reduces the irritating action on eyes or skin. The whiteness of skin-bleach disappears in a few hours. Prolonged contact, without subsequent washing, may produce blisters and light burns. These are the only physiological effects, and, therefore, make 90 per cent  $H_2O_2$  a very acceptable propellant from the toxicity standpoint. The decomposition products, steam and oxygen, are nontoxic.

#### Comparison with Other Oxidizers

Important factors in the selection of an oxidizer are its density, stability in storage at ambient temperatures, handling procedures, and the commercial availability of the materials of construction required for storage and handling. Comparison of these factors for 90 per cent

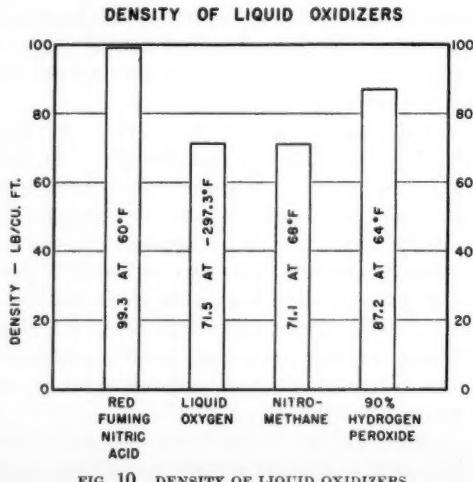


FIG. 10 DENSITY OF LIQUID OXIDIZERS

TABLE 4 COMPARATIVE PROPERTIES OF OXIDIZERS

Oxidizer	Boiling point, F	Maximum storage temperature, F	Vapor pressure, mm, Hg
	+130	+100	129 at ambient temperature 2060 at 150 F
Liquid oxygen	-297.35	-297.35 at atm pressure	49.713 atm at -181.8 F
Nitromethane	+214	+120	8.71 at 32 F
90% H <sub>2</sub> O <sub>2</sub>	+287.6	+130	0.6 at 41 F
			35.9 at 70 F
			1.5 at 68 F
			221 at 150 F
			18.1 at 140 F

TABLE 5 MATERIALS OF CONSTRUCTION FOR HANDLING CHEMICAL OXIDIZERS

Oxidizer	Metals	Plastics	Others
RFNA	304, 347 stainless steel; aluminum	Teflon	Glass; ceramics
Liquid oxygen	Stainless steel, aluminum, Cu, brass, bronze, monel, etc.	Rubber, many common plastics	Glass, ceramics
Nitromethane	Stainless steel, aluminum,	Bakelite	Glass, ceramics
90% H <sub>2</sub> O <sub>2</sub>	300 series stainless steel; aluminum; tin	Teflon, polyethylene, Kel-F	Glass, ceramics

H<sub>2</sub>O<sub>2</sub>, red fuming nitric acid, liquid oxygen, and nitromethane clearly indicates that 90 per cent H<sub>2</sub>O<sub>2</sub> compares most favorably with these oxidizers for ease and safety of storage and handling.

*Density:* Fig. 10 is a comparison of the densities of these oxidizers. It is evident that use of 90 per cent H<sub>2</sub>O<sub>2</sub> permits a favorable high weight per volume factor of oxidizer.

*Storage and Handling:* Ninety per cent H<sub>2</sub>O<sub>2</sub> can be safely stored at relatively high ambient temperatures. As shown in Table 4, the boiling point, recommended storage temperatures, and vapor pressures of 90 per cent H<sub>2</sub>O<sub>2</sub> show superior operating potential. Its extremely low vapor pressure has distinct advantages in ready storage considerations.

Exposure to light and clean air leaves 90 per cent H<sub>2</sub>O<sub>2</sub> structurally undisturbed. On the other hand these conditions cause red fuming nitric acid to fume and slowly decompose with slight absorption of moisture. Oxygen, of course, vaporizes rapidly and simultaneously condenses water vapor. Last of all, such exposure sensitizes nitromethane to detonation by shock.

A study of the combustibility of these oxidizers reveals that red fuming nitric acid and liquid oxygen, like 90 per cent H<sub>2</sub>O<sub>2</sub>, are noncombustible

but support the combustion of organic materials. Nitromethane, on the other hand, has a flash point at 112 F.

When the available materials for storage and handling operations are reviewed, it is apparent that the needs of all these oxidizers are equally satisfied. A number of these materials are tabulated in Table 5.

Storage tanks, tank cars, and drums are used for the storage and transportation of all of these oxidizers. For oxygen the vessels require insulated vacuum jackets.

*Toxicity:* Ninety per cent H<sub>2</sub>O<sub>2</sub> and liquid oxygen are not toxic; nor do they yield toxic decomposition products to contaminate the areas of operation. On the other hand, red fuming nitric acid and nitromethane are both sources of such hazards. The upper limits of nontoxic concentration of the air with NO<sub>2</sub> of red fuming nitric acid is 10-25 ppm; the low limit for fatality is 300 ppm. A concentration of 750-1000 ppm of nitromethane in air may form a lethal dose. Definitely safe concentrations exist only below 0.5-1 per cent by volume in air.

Thus, gas masks are required for spillage and decomposition of red fuming nitric acid and nitromethane, but are totally unnecessary for liquid oxygen or 90 per cent H<sub>2</sub>O<sub>2</sub>.

The handling of all oxidizers requires use of safety gloves, goggles, boots, aprons, etc. In the case of nitromethane, only sparkproof tools may be used within the area.

No health supervision of personnel is required with either liquid oxygen or 90 per cent H<sub>2</sub>O<sub>2</sub>. This contrasts with periodic medical examinations and rotation of personnel prescribed for installations employing red fuming nitric acid and nitromethane.

It is quite apparent that the storage and handling problems of 90 per cent H<sub>2</sub>O<sub>2</sub> are no greater than those for other common oxidizers. In fact, it has distinct advantages in ready storage and under handling conditions where unskilled personnel might be employed.

### **Concentrated H<sub>2</sub>O<sub>2</sub> as an Oxidant in Liquid-Fuel Rockets**

The discussion thus far has presented the properties and the storage and handling characteristics that mark concentrated H<sub>2</sub>O<sub>2</sub> as an oxidizer in liquid-fuel propellant systems. Many fuels can be readily employed with H<sub>2</sub>O<sub>2</sub> in bipropellant systems. Thus, some fuels burn spontaneously when mixed with concentrated H<sub>2</sub>O<sub>2</sub>, with or without an ignition catalyst.

The prime known example of the H<sub>2</sub>O<sub>2</sub> fuel system is the Walter 509A2 motor for the German Messerschmitt ME-163B rocket fighter. In this motor, a fuel mixture of 30 per cent hydrazine hydrate, 57 per cent methyl alcohol, and 13 per cent water containing KCu(CN)<sub>6</sub> ignition catalyst was burned with 80 to 83 per cent H<sub>2</sub>O<sub>2</sub>. A maximum thrust of 3770 lb at sea level was developed. Sufficient propellants were carried for a climb

TABLE 6 CALCULATED BIPROPELLANT PERFORMANCE CHARACTERISTICS

Part 1— $H_2O_2$  Fuel Systems

Propellants	Mix-ture ratio	Cham-ber pres-ure, psi	Spe-cific thrust, second	Dens-ity	Den-sity im-pulse	Chamber tem-perature, F	Ex-hau-st veloci-ty, fps
Hydrogen peroxide— Hydrazine	1.45	300	247	1.23	303	4450	7950
Hydrogen peroxide— ANF-58 fuel	5.75	300	233	1.28	298	4680	7510
Hydrogen peroxide— Ethyl alcohol (92.5)	3.4	300	229	1.22	279	4440	7380
Hydrogen peroxide— Nitromethane	0.67	300	227	1.27	288	4890	7310
Hydrogen peroxide— 87%—Nitromethane	1.0	300	229	1.28	293	4610	7380
Hydrogen peroxide— 87%—Methyl alcohol	5.7	300	199.1	1.243	248	3520	6420
Hydrogen peroxide— 87%—Methyl alcohol	3.7	300	225	1.19	268	4130	7250

## Part 2—Other Oxidizer Fuel Systems

Liquid oxygen—	5.33	340	335	0.33	110	4290	10800
Liquid hydrogen							
Liquid oxygen— Ammonia	1.4	300	255	0.98	249	4951	8220
Liquid oxygen— Hydrazine	0.50	300	259	1.05	272	4500	8350
Liquid oxygen— Hydrazine	0.67	300	267	1.09	282	5090	8600
Liquid oxygen— Ethyl alcohol	1.5	300	243	0.966	235	5250	7810
Liquid oxygen— Nitromethane	0.08	300	225.5	1.139	256	4700	7260
Liquid oxygen— Gasoline	2.5	300	242	0.965	236	5470	7780
Liquid oxygen— Methyl amine	2	300	266	0.985	262	5540	8560
Red fuming nitric acid—Aniline	3	300	221	1.37	303	5020	7090
White fuming nitric acid—Furfuryl alcohol	1.9	300	214	1.37	293	5020	6890
Mixed acid—Mono-ethyl aniline	4.55	338	210	1.396	293	4650	6760
Nitric acid—Hydrazine	1.6	300	243	1.28	311	....	7810
Nitric acid—Liquid hydrogen	12.6	300	298	0.61	182	....	9600

Note: Partly reproduced from "Rocket Propulsion Elements," by G. P. Sutton.

TABLE 7 CALCULATED MONOPROPellant PERFORMANCE CHARACTERISTICS

Propellant	Chamber pressure, psi	Exhaust velocity, fps	Specific impulse		Density impulse, Sec	Exhaust temperature, F	Mean molecular weight, lb/mol	Specific heat ratio
			Dens	Sec				
100% H <sub>2</sub> O <sub>2</sub>	300	4700	145	1.45	212	1790	23	1.25
90% H <sub>2</sub> O <sub>2</sub>	300	4250	131	1.39	186	1360	22	1.256
Nitromethane	300	7040	218	1.14	248	3980	20	1.25
100% H <sub>2</sub> O <sub>2</sub>	515	4990	155	1.45	224	1804	23	1.278
100% H <sub>2</sub> O <sub>2</sub>	441	4900	152	1.45	220	1804	23	1.273

Note: Partly reproduced from "Rocket Propulsion Elements," by G. P. Sutton.

to 40,000 ft in approximately 2.4 min followed by 7.6 min at a top speed of 500 mph in level flight. An important feature of the motor was the use of part of the H<sub>2</sub>O<sub>2</sub> to power a turbine which drove the propellant supply pumps. Cooling of the rocket nozzle was provided by circulating the fuel through a cooling jacket prior to introduction into the combustion zone.

Theoretical performance calculations for several of the H<sub>2</sub>O<sub>2</sub> fuel combinations are presented in Part 1, Table 6. Anhydrous H<sub>2</sub>O<sub>2</sub> and anhydrous hydrazine in the optimum weight ratio of 1.45 yield the maximum specific impulse of 246.6. This system will readily ignite without benefit of any igniter or ignition promotor. It is characterized by reasonably low combustion and exhaust temperature and high density of working gases. Use of commercially available 90 per cent H<sub>2</sub>O<sub>2</sub> instead of the theoretical 100 per cent H<sub>2</sub>O<sub>2</sub> reduces the system performance slightly.

Similar theoretical performance data for other oxidizer fuel systems are presented in Part 2 of Table 6. Note that the use of H<sub>2</sub>O<sub>2</sub> as an oxidizer compares favorably in performance with liquid oxygen, nitric acid, and mixed acids. Based on specific impulse, the H<sub>2</sub>O<sub>2</sub> fuel systems compare favorably with other bipropellant systems except those involving liquid hydrogen as the fuel. The density impulse comparison also indicates favorable range characteristics. The performance of H<sub>2</sub>O<sub>2</sub> and the reasonably common fuel AN-F-58 is comparable to the two most common systems in use today, that is, red fuming nitric acid-aniline and liquid-oxygen-ethylalcohol.

Concentrated H<sub>2</sub>O<sub>2</sub> may also be considered as a monopropellant for rocket motors since it readily decomposes to yield a large volume of hot gases. However, as can be seen from Table 7, the specific im-

pulse of 100 per cent  $H_2O_2$  even at 500 psi chamber pressure is inferior to that of pure nitromethane at a much lower chamber pressure. Nevertheless, due to its handling characteristics the Germans used  $H_2O_2$  in so-called "cold drive" units. Generally the system used was aqueous  $H_2O_2$ -aqueous calcium permanganate. Examples of units utilizing this system were the Focke-Wolf ATO Fw 56 which developed 650-lb thrust for 30 sec, pilot-controlled units for the Henkel He 112 and He 126 Rocket Motors which developed a maximum of 2200-lb thrust and 1100-lb thrust, respectively, and the Messerschmitt Me-163A rocket ship with a maximum thrust of 1650 lb and a top speed of 637 mph. The British de Havilland Sprite assisted take-off unit, recently announced, utilizes 80 per cent  $H_2O_2$  and calcium or sodium permanganate to produce a thrust of 55,000 lb for 9-12 sec.

### Concentrated $H_2O_2$ for Auxiliary Power Generation

Concentrated  $H_2O_2$  as a monofuel will drive turbines to power main propellant pumps in rocket ships. The Germans used an  $H_2O_2$  auxiliary generator in the V-2 missile although the main rocket was a liquid oxygen-ethyl alcohol system.

In this generator the  $H_2O_2$  and aqueous permanganate solution were passed at a gas pressure of approximately 300 psi into a chamber which supplied decomposition products to drive a 500-hp double-stage reaction

turbine. This in turn drove the oxygen and alcohol pumps. A high-pressure gas cylinder bank was required to supply the  $H_2O_2$ . Turbine pressure ratio was 20 to 1 with exhaust of the harmless gases to the atmosphere.

The efficiency of such a turbine unit may be low and the cost of working gases fairly high. Yet the saving in weight, space, and ease of handling and operation over a gas pressurizing system was considerable. Compared to other systems, the decomposition of concentrated  $H_2O_2$  without combustion is undoubtedly the simplest and most reliable.

Using 90 per cent  $H_2O_2$ , the theoretical horsepower available to a heat

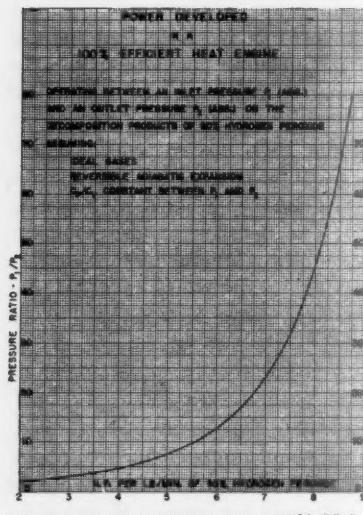


FIG. 11 POWER PRODUCTION—90%  $H_2O_2$  MONOPROPELLANT

engine per pound of working fluid has been calculated from reliable thermodynamic data for a range of inlet to exhaust pressure ratios from 1 to 80, Fig. 11. A 500-hp turbine of 50 per cent mechanical efficiency would require a 90 per cent H<sub>2</sub>O<sub>2</sub> flow rate of 135 lb per min.

The Germans also used H<sub>2</sub>O<sub>2</sub> generator power for launching the ramjet propelled V-1 buzz bomb. This piston-type launcher which was adequately described by F. Bellinger, et al., utilized 80 to 85 per cent H<sub>2</sub>O<sub>2</sub> and calcium or sodium permanganate solution as decomposition catalyst. It developed a speed of 250 mph in 150 ft of travel in 0.75 sec with an acceleration of 483 fps. The instantaneous work being done at the end of the period was 55,000 hp and the required gas generation at that point was 15,000 cu ft per min at 850 psi. Flow rate of 90 per cent H<sub>2</sub>O<sub>2</sub> to produce this power and gas flow is 14,500 lb per min at 20 C (68 F).

### Conclusion

This discussion has analyzed a number of characteristics of 90 per cent H<sub>2</sub>O<sub>2</sub>. These definitely enhance its importance as a rocket bipropellant, for it has been indicated that its application toward this function is supported by its physical, chemical, and energy characteristics. Finally, these advantages are further supported by its relative ease of safe storage and handling.

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## HANDLING OF LIQUID OXYGEN

By G. E. Simpson

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The commercial oxygen industry during the last 20 years has developed principles for handling bulk oxygen and accumulated a fund of experience which should be helpful in solving liquid-oxygen handling problems in rocket technology. This paper reviews experience and states principles pertinent to oxygen handling and equipment design.

**E**XPERIMENTS in this country with liquid oxygen as a rocket-fuel oxidant were begun more than 20 years ago. Wide publicity about the process however probably dates back less than five years to the use of a liquid-oxygen-alcohol rocket bomb as a standard item of ordnance by the dying German military machine in Europe.

It is well known that oxygen gas is widely used throughout the United States for industrial and medical purposes, but it has come as a surprise to many persons becoming engaged in rocket engineering to learn that a system has been in commercial use in this country for nearly 20 years for producing, shipping, and storing oxygen as a liquid for use as oxygen gas.

This system of liquid-oxygen production and distribution, developed to a continent-wide supply for commercial oxygen gas, now makes possible supplying this product to projects engaged in the study of rocket engineering. Facilities for production, transport, and storage area are already available for supplying liquid oxygen at remote and widely separated points in the United States.

### Properties and Uses of Oxygen Gas

A brief review of some of the properties of oxygen will be useful to this discussion on the handling of the product in liquid form. Oxygen is a colorless, odorless, tasteless gas that makes up about 21 per cent of the earth's atmosphere. It is nontoxic and noncombustible, and is accepted by the Bureau of Explosives for Railroad Interchange.

Although noncombustible, oxygen actively supports combustion, a property which is the basis for its commercial use. Combined with acetylene, oxygen gives the hottest gas flame known, a flame that has many industrial applications for the welding and treating of metals. The oxyacetylene flame, combined with a separate stream of high-purity oxygen, is used for cutting iron and steel. Within recent years large quantities of oxygen have

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been used for breathing purposes in medical applications and in high-altitude flying. All of these applications utilize oxygen in gaseous form.

### Oxygen Production

The principal method for oxygen manufacture is by liquefaction and distillation of air, a process that was originally developed late in the nineteenth century. Fundamentally it consists of the compression and progressive cooling of purified air to accomplish liquefaction, followed by binary distillation.

A variety of cycles have been developed to accomplish the liquefaction, some using external refrigeration, some using the Joule-Thomson effect entirely, and others combining this principle with expansion engines. The liquefied air produced in this way is distilled to a commercial product that is 99.5 per cent pure oxygen. The distillation operation itself takes place at slightly above atmospheric pressure.

Another process that is used to a minor extent for oxygen production is the electrolytic separation of water to give hydrogen and oxygen, both as gaseous products. Power consumption is high, and oxygen produced by this method is a by-product from the production of hydrogen.

### Oxygen Distribution

Until the early 1930's oxygen was transported in the familiar steel cylinders and today much oxygen is still transported in these containers. In these cylinders the oxygen is compressed to 2200 psi at 70 F. The capacity at the pressure of 2200 psi of the most common size is 244 cu ft of oxygen gas at atmospheric pressure and 70 F. Cylinders with a number of other capacities are also in regular use. All these cylinders must be manufactured in accordance with I.C.C. regulations.

The cylinder-distribution system is a practical one for relatively small users. With cylinder distribution however a high ratio of container weight to product weight exists. For example, with the 244 cu ft size, approximately 130 lb of container must make the round trip to deliver about 20 lb of product.

With the increase in oxygen demand in the early 1930's, bulk methods of oxygen distribution became imperative. As a result of the development of bulk-distribution methods, large industrial plants and hospitals are equipped with oxygen pipe lines feeding all major use points.

One of the schemes for distributing oxygen in bulk consists of mounting large cylinders or high-pressure tubes on trailers. These trailers, when charged with oxygen gas at the producing plant, are then connected through suitable pressure-reducing regulators to a pipe-line system at the point of use. By changing the size or the number of tubes, trailers of various capacities have been developed, with 40,000 cu ft being about the maximum.

By this method an improvement in the ratio of container-weight to product-weight is accomplished, and cylinder handling is eliminated.

Another plan of bulk distribution consists of transporting the oxygen in liquid form. This liquid system was inaugurated commercially in 1932 after an intensive five-year research and development program. Liquid oxygen is shipped from large capacity producing plants by either railroad tank car or tank truck. The capacity of the railroad tank car is approximately 6500 gal, or the equivalent of about 750,000 cu ft of oxygen gas at standard pressure and temperature. Trucks vary in size from 60,000 to 300,000 cu ft capacity, or from 520 to 2600 gal.

In the distribution of oxygen in liquid form, the ratio of container-weight to product-weight is vastly improved over the gaseous distribution system. One cubic foot of liquid will evaporate to approximately 862 cu ft of gas at standard conditions. The liquid oxygen weighs 71.5 lb per cu ft and is transported at atmospheric pressure. The temperature of the liquid is -297.4 F (-183 C). Equipment for handling the liquid oxygen includes storage tanks, pumps, and evaporation units.

### Distribution at Point of Use

At the point of use, the liquid-distribution system takes two basic forms, although modifications of the forms are used. The essential difference between the two forms is that, at the point of use in one system, the oxygen is stored as a liquid and converted to gas as needed by the user. In the other, the oxygen is transported as a liquid, but is stored as a gas.

If consumption is large, the oxygen is delivered by either tank car or truck, and is pumped into pressure vessels or into a storage tank. The liquid is held in the pressure vessels at a pressure of about 150 or 200 psi, converted to gas as needed, and supplied to the user's pipe line at a pressure high enough to provide the desired working pressure at each outlet. Storage tanks ranging in size up to 1 $\frac{1}{2}$  million cu ft are used as a reserve for filling the pressure vessels.

In the second method, for users in the middle range, the oxygen is stored as a gas at 2200 psi at 70 F in high-pressure receivers. These receivers are charged by means of special trucks which transport the oxygen as liquid; pump the liquid into a conversion unit on the truck; and vaporize it to a gas for storage. Capacities of these storage systems vary anywhere from about 25,000 to 100,000 cu ft. The receivers are connected by means of suitable pressure-control equipment to the user's oxygen pipe line, which extends to all significant consumption points in the user's plant.

### Handling Liquid Oxygen

The handling of liquid oxygen, in common with many other industrial processes, presents certain problems and possible hazards. These stem

from three general sources: (1) chemical activity of oxygen; (2) extremely low temperatures involved; and (3) volume change that results from the introduction of heat to the liquid.

Since oxygen is used commercially only in the gaseous form, not many people have had a practical interest in the principles or practices of handling oxygen in liquid form. With the advent of the use of this product in rocket engineering, however, the interest in this subject is broadening.

The remainder of this paper will review some of the principles and pertinent information accumulated during more than 20 years of experience in the production and distribution of liquid oxygen.

Several specific examples and data will be used to illustrate these principles. One of the things which experience has shown is that materials and designs for liquid-oxygen use should be thoroughly tested before putting them into practice. It is a theme that needs continually to be stressed in this type of work; namely, that designs and materials for liquid-oxygen production and service must be tested under the service conditions to be imposed before they can be accepted.

One of the possible sources of hazards is that resulting from the chemical affinity of oxygen for certain materials. It has been demonstrated by long experience that liquid oxygen is chemically stable as long as there is complete absence of contaminating organic matter. It is imperative that oxygen equipment be clean. All vessels or piping that are to conduct oxygen must be carefully cleaned before use, and complete provision made to prevent organic material from coming in contact with the product.

### **Gas Itself is not Combustible**

Although oxygen itself is not combustible, the gas evolved from the vaporization of liquid oxygen will support rapid combustion. Oxygen should therefore be kept away from flames and from flammable materials.

It is best to keep liquid-oxygen containers in areas where adequate ventilation is assured, and thus avoid potentially dangerous oxygen concentrations. Closed areas or depressed pockets provide the opportunity for concentrations of cold oxygen gas to collect. Such concentrations may cause materials like cotton, wool, and other porous organic matter to burn violently if ignited, even several minutes after exposure to the oxygen atmosphere.

The excessively low temperatures of liquid oxygen present a hazard to persons working with the product unless proper safeguards are taken. Careful training of all personnel in proper handling methods is essential to minimize accidental spilling, both to avoid damage due to the coldness of the liquid, and the concentrations of the gas.

The only physiological effect is that due to the low temperature. Liquid spilled on the flesh produces an effect similar to a scald or burn. Not only

the liquid but any unprotected surfaces of metal carrying the liquid, consequently extremely cold, offer potential hazards. Suitable protective clothing, including goggles and leather gloves, should always be worn by personnel handling the liquid in an open system.

### Equipment Design Considerations

A second factor that results from the extremely cold temperatures is the structural one. Many materials, including the common ferrous alloys, become quite brittle at low temperature. The ductility and impact values are greatly reduced so that for most engineering designs, such materials are not considered suitable. It is interesting to note however that the tensile strength of most materials will increase considerably at low temperatures, reaching values from 50 to 200 per cent higher than at the normal temperatures.

Many nonferrous metals and alloys maintain good ductility at low temperatures. Both tensile strength and yield point of such materials show an increase. Among the ferrous alloys, the nickel-chromium alloys behave similarly to the nonferrous metals. Among the most common of these alloys is the familiar 18-8 stainless steel. The nonferrous alloys and the nickel-chromium alloys maintain their impact value to an effective degree at low temperatures, and for many applications make acceptable structural materials. It is important however to consider carefully all the service conditions that will be imposed in selecting an alloy. By "all service conditions" are meant those present during its low temperature service, during the time the equipment is empty, and during the period while it is being cooled down.

The coldness of liquid oxygen makes necessary careful considerations from a design standpoint for other reasons than the mechanical properties of the equipment materials. The boiling point of liquid oxygen at atmospheric pressure is -297.4 F (-183 C). Under these conditions any heat which flows into the liquid from its surroundings vaporizes a portion of it.

It is important that all parts of equipment that can be isolated while containing liquid, or cold vapor, be provided with safety relief valves or other devices to avoid any excessive pressure rise.

### Insulation Required

Successful design of the equipment also requires insulation. Factors that must be considered in choosing methods of insulating are low thermal conductivity, specific heat, packed density, and, with liquid oxygen, nonflammability. Exposed cold surfaces and poorly constructed insulation casings will condense and freeze atmospheric moisture. Such evidences of poor design and construction not only increase evaporation and loss of liquid, but

also introduce possible hazards involving structural failure because of the weight of the ice.

Fibers and powders commonly used for insulation are rock wool, glass wool, diatomaceous earth, and magnesia cement. Cork and hair felt introduce the problem of flammability, although they have the property of low density.

In cases where vaporized liquid would constitute an excessive loss, means must be adopted to reduce the flow of heat. In addition to as complete insulation as possible, either at atmospheric pressure or under vacuum, design should eliminate as many paths for heat conduction as possible. Methods for increasing the resistance to heat conduction should be employed wherever connections are required.

Liquid-oxygen storage tanks in sizes from 3 to 13,000 gal have been produced using a patented method of insulation. In this scheme, the liquid-oxygen vessel is insulated by a powder and the space occupied by the powder is also under a high vacuum. Percentage loss from these vessels is in general approximately 25 per cent of the loss of vessels of similar capacity and insulation thickness without the vacuum. In the large sizes of vacuum-powder insulated vessels, daily loss values of about  $\frac{1}{2}$  of 1 per cent of the capacity have been realized.

### **Selection of Valves and Shaft Packings**

Another important consideration in design for liquid-oxygen service is the selection of valve and shaft packings. Here again, the important principles of careful consideration of service conditions and thorough testing of materials are of paramount importance. In addition to the usual requirements for packing service, materials for low-temperature service must maintain a proper degree of resilience at operating temperatures. Frequently, improvement of the working conditions can be obtained by the use of extended housings so that the packing operates in a relatively warm area.

Packing materials must be noncombustible, a requirement that eliminates packings made of cotton or linen fibers and the use of oily materials either as binders or lubricants. One material that has proved successful in many circumstances is pure clean asbestos in combination with clean shredded lead.

It should be stressed that the special problems encountered in rocket engineering are often not solved by existing and proved equipment or technology. The foundations which have been laid in the normal development of a commercial oxygen industry have assured an ample supply of liquid oxygen for extensive experimental projects. Furthermore, those experienced in the handling of liquid oxygen in transport are in a position to make contributions toward the solution of the new problems which have and which will arise in the utilization of this product in the new field of rocket engineering.

# NITROGEN TETROXIDE AS AN OXIDIZER IN ROCKET PROPULSION

By Douglas H. Ross

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Physical and chemical properties, methods of preparation and handling, and some typical reactions of nitrogen tetroxide are discussed with emphasis on those of greatest interest to rocket engineers.

WITHIN recent years nitrogen tetroxide has become readily available at low cost, and research on its use has been inaugurated along many different lines. One of the most interesting of them has been in the field of rocket propulsion. It is the purpose of this paper to describe the properties of nitrogen tetroxide with special emphasis on those properties allied to rocket fuels.

## Physical Properties

Nitrogen tetroxide ( $N_2O_4$ ), also known as nitrogen peroxide or liquid dioxide, is a heavy brown liquid at ordinary temperatures containing about 30 per cent nitrogen and 70 per cent oxygen. Product is available in pure form containing 0.1 per cent water or less and only a trace of lower nitrogen oxides. Physical properties are shown in Table 1. Fig. 1 shows a plot of the vapor pressure-temperature relation for nitrogen tetroxide.

TABLE 1 NITROGEN TETROXIDE CONSTANTS

Molecular weight ( $N_2O_4$ ).....	92.02
Boiling point.....	21 C
Freezing point.....	-11.3 C
Critical temperature.....	158 C
Latent heat of vaporization.....	99 cal/g at 21 C
Critical pressure.....	99 atm
Specific heat of liquid	0.36 cal/g, -10 to +20 C
Density of liquid (under its own vapor pressure) (water = 1 at 4 C).....	1.45 at 20 C
Density of gas.....	3.3 g/liter, 21 C, 1 atm

Presented at the 1949 Annual Convention of the AMERICAN ROCKET SOCIETY, Hotel Statler, New York, N. Y., Nov. 27-Dec. 2, 1949.

The product is an equilibrium mixture:



with substantially complete conversion to the monomolecular form above 140 C. Dissociation values are given in Fig. 2.

## Unloading and Handling

Wet nitrogen tetroxide is corrosive to steel, but when dry (0.1 moisture) can be stored and shipped satisfactorily in steel containers. The vapor pressure is low at ordinary temperatures, 2 atmospheres absolute at about 35 C (95 F). This means that low-pressure containers are suitable for transfer and storage.

Nitrogen tetroxide at present can be shipped only in high-pressure seamless-steel cylinders, Specifications 3-D and 3-A. Fig. 3 shows details and dimensions of the 125-lb cylinder for shipments. Fig. 4 shows a number of containers in which the product was shipped for one of the Armed Services during World War II.

I.C.C. shipping regulations require a plug for the cylinder closure along with the gasketed protective cap. For unloading purposes however a valve may be attached to the cylinder opening by removal of the plug after cooling contents to between 0 and 10 C. A caulking and lubricating compound composed of water glass and powdered graphite is effective on threaded joints. Care should be taken to avoid the use of hydrocarbon lubricants where contact with nitrogen tetroxide is possible. Carbon steel or stainless steel valves may be used. For continued use a stainless steel (18-8 type) valve will give better service than a carbon steel valve due to the elimination of valve stem corrosion caused by a leaking packing gland.

Nitrogen-tetroxide gas, like NO and  $\text{N}_2\text{O}_3$ , is toxic and should not be breathed even in dilute concentrations. When transferring from shipping container to storage cylinder, operation should be conducted out-of-doors. An "all-service" gas mask should be worn as an added precaution. For confined spaces, an approved hood or helmet-type mask having an auxiliary oxygen supply should be used. When handling liquid or gaseous nitrogen tetroxide, goggles always should be worn properly fitted over the eyes, also synthetic (neoprene type) rubber gloves.

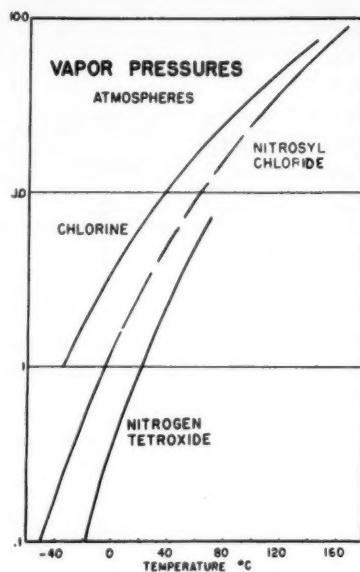


FIG. 1 VAPOR PRESSURE COMPARISONS

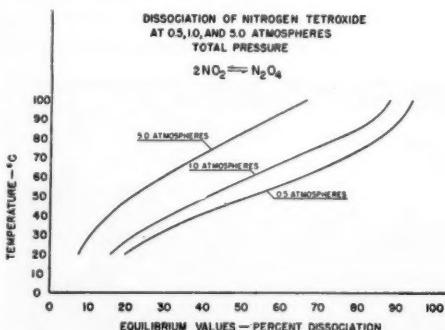


FIG. 2 DISSOCIATION VALUES

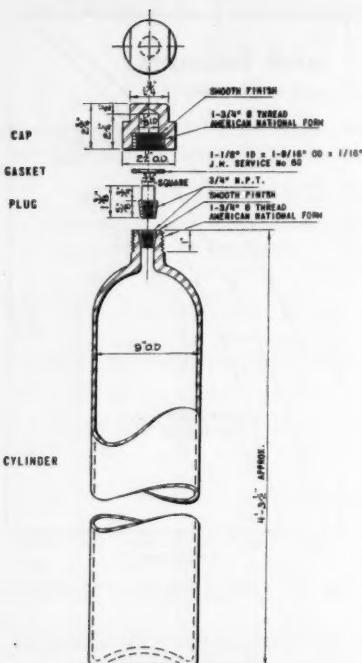


FIG. 3 NITROGEN TETROXIDE CYLINDER;  
CAPACITY 125 LB; MATERIAL IS CARBON  
STEEL

gen tetroxide. Those interested in pursuing this phase of the subject are referred to the excellent report by Riebsomer (2). The following chemical reactions may be of specific interest to rocket-fuel engineers.

Nitrogen tetroxide is the mixed anhydride of nitric and nitrous acids, and resembles ozone and hydrogen peroxide in many of its reactions.

*Additional Reactions:* Nitrogen tetroxide is known to react with un-

saturated compounds, e.g., olefins, to form adducts of various types depending on the reaction conditions and the type of compound. Thus, nitrogen tetroxide in some cases appears to act as  $\text{NO}_2\text{-NO}_2$ , forming thereby dinitro compounds or nitro-

<sup>1</sup> Numbers in parentheses refer to bibliography listed on page 31.

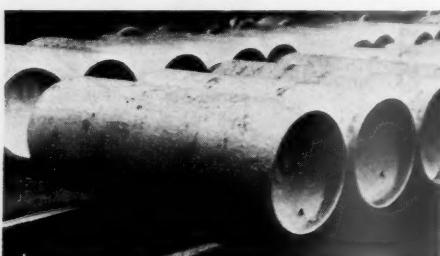


FIG. 4 TON CONTAINERS FOR NITROGEN TETROXIDE

## Preparation

Several laboratory methods have been suggested for the preparation of nitrogen tetroxide as shown in Table 2.

TABLE 2 PREPARATION OF NITROGEN TETROXIDE

- 1  $3\text{NaNO}_2 + 2\text{HNO}_3 = 3\text{NaNO}_3 + 2\text{NO} + \text{H}_2\text{O}$
- 1a  $2\text{NO} + \text{O}_2 = 2\text{NO}_2$
- 2  $3\text{NOCl} + 2\text{H}_2\text{O} = 3\text{HCl} + \text{HNO}_3 + 2\text{NO}$  (at low acidity)
- 2a  $2\text{NO} + \text{O}_2 = 2\text{NO}_2$
- 3  $2\text{Cu}(\text{NO}_3)_2 \xrightarrow{\text{Heat}} 2\text{CuO} + 4\text{NO}_2 + \text{O}_2$
- 4  $2\text{NOCl} + \text{O}_2 \longrightarrow \text{N}_2\text{O}_4 + \text{Cl}_2$  (1)
- 5  $4\text{NH}_3 + 5\text{O}_2 \longrightarrow 4\text{NO} + 6\text{H}_2\text{O}$
- 5a  $2\text{NO} + \text{O}_2 \longrightarrow \text{N}_2\text{O}_4$

For large scale commercial production, methods such as 1, 4, and 5 can be used without difficulty (1)<sup>1</sup>.

## Reactions

This paper will not attempt to review in detail the many different chemical reactions involving nitrogen tetroxide.

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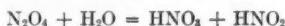
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nitrites. For example, recent British developments have led to methods for preparation of dinitro derivatives of the lower olefins such as propylene, the products being cited as useful in explosives. In other cases nitrogen tetroxide appears to act as  $\text{NO-NO}_3$  forming nitrosonitrates. This behavior as  $\text{NO-NO}_3$  is also encountered when ionic reactions are conducted in nitrogen tetroxide as a polar solvent in which  $\text{NO}^+$  and  $\text{NO}_3^-$  ions are present (3, 4).

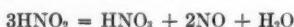
These reactions appear to merit exploratory research with a view toward developing new organic products.

*Nitration of Organic Compounds:* Nitrogen tetroxide may be of use in nitrating organic compounds. In some instances, for example, nitration of benzene, toluene, and aliphatic hydrocarbons, the reaction is slow at moderate temperatures and at high temperatures side reactions such as oxidation tend to become prominent.

Nitrogen tetroxide reacts with water as follows:



The nitrous acid undergoes decomposition:



Over-all, two thirds of the  $\text{N}_2\text{O}_4$  goes to form nitric acid, the other third may be oxidized with air or oxygen to re-form  $\text{NO}_2$  or  $\text{N}_2\text{O}_4$ .

*Oxidation:* From its formula, it is evident that nitrogen tetroxide carries about 70 per cent oxygen. Under mild conditions half of this oxygen can be utilized and under more vigorous conditions, such as prevail in the combustion chamber of a rocket motor, all of the oxygen is available.

### Applications

It is as an oxidizer that nitrogen tetroxide is of most value to the rocket engineer. The principle of using nitrogen tetroxide as an oxidant has been known for many years.

The power of a high explosive made with nitrogen tetroxide and a suitable hydrocarbon was studied by Turpin, a French engineer, in 1880 (5). The development by Paulet in 1895 of a practical rocket motor using liquid propellants was one result of Turpin's research (6). In another case, the French in 1914 devised a crude drop bomb containing two compartments separated by a diaphragm. One compartment was filled with nitrogen tetroxide and the other with gasoline which mixed in flight upon rupture of the diaphragm. This worked poorly and the project was abandoned.

In this country, N. M. Hopkins carried on a series of studies which added substantially to the data on nitrogen-tetroxide explosives, particularly the range in which mixtures developed maximum explosive power (7). He also developed several devices for ordnance purposes, Fig. 5.

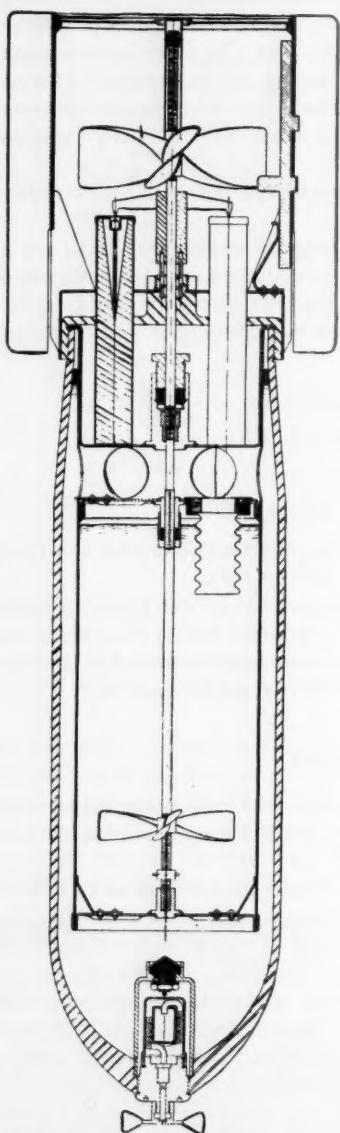


FIG. 5 SPECIAL DROP BOMB USING NITROGEN TETROXIDE

At about the same time, but independently, Strettbacher (8) reported on the properties of  $N_2O_4$ -toluene,  $N_2O_4$ -nitrobenzene, and  $C(NO_2)_4$ -toluene mixtures. These are among the products most sensitive to shock in the list, but are useful in that they have high heats of explosion and develop high temperatures on explosion. The velocity of the explosive wave for the  $C(NO_2)_4$ -toluene mixture was the highest of any compound or mixture noted (9300 meters per sec.).

Nitrogen tetroxide has been used experimentally by several different groups in rocket research during the past few years. The GALCIT group undertook the development of JATO units powered with liquid fuels to meet thrust requirements for longer time intervals not readily obtainable with solid fuels. Both liquid and solid JATO units were tested by the AAF on most of its standard aircraft, including P-38, P-40, P-59, AX20, B-17, B-24, and B-29 (9).

Early in 1941 the Navy's Bureau of Aeronautics established a rocket-research group at Annapolis, Md., where intensive work primarily on long-burning liquid-propellant units was undertaken. As a result this group on Sept. 23, 1942, made the Navy's first JATO take-off using a liquid-fueled rocket designed by the late Dr. Robert H. Goddard.

The Navy was interested in JATO for two purposes: First, to shorten the take-off runs of carrier-based planes; and second, to enable large flying boats to take off in restricted areas, in rough waters,

or in an overload condition.

In order to proceed rapidly with both liquid and solid-propellant rocket developments, the Bureau of Aeronautics set up a program including, in addition to the Annapolis group, the research organization of the Aerojet Engineering Corporation, Pasadena, Calif., and Reaction Motors, Inc., Pompton Plains, N. J.

We know now that during this same period, the Germans were pushing ahead with a similar program for the development of rocket motors (10).

Rocket applications have advanced far beyond this early stage and currently many different and exciting developments are taking place. Most of the details are classified and cannot be released for publication.

A brief analysis of the properties of nitrogen tetroxide which make it valuable as an oxidizer in rocket propulsion follows.

*Ease of Handling:* A rocket-fuel oxidizer should possess high chemical stability, a high density, a low freezing point, and a reasonably low vapor pressure. It should not be susceptible to sabotage by catalytic decomposition, nor should it present unusual storage difficulties. Nitrogen tetroxide generally fulfills these requirements.

For applications involving greater ambient-temperature variations than encountered in high-temperature zones, this oxidizer may be modified in several ways; e.g., a low-freezing oxidant is described in a patent issued to Lawson (11).

*Corrosion:* A rocket-fuel oxidizer should be substantially noncorrosive so that transportation, storage, and use are not dependent on special alloys but can be accomplished with simple steel components (12). Nitrogen tetroxide fulfills this requirement. In addition, its corrosion characteristics are such as to minimize the destruction of strategic materials during an emergency.

*Availability:* An oxidizer for general propulsion use should be available, or potentially available in good supply. Assuming only 10 per cent of all ammonia were oxidized to nitrogen tetroxide, this country has a combined potential of about  $\frac{1}{2}$  million tons annually. See Table 3.

*Energy:* The rocket motor operates by generating high-temperature and high-pressure gases which are subsequently expanded through a nozzle to obtain a high jet velocity which produces the reactive force or thrust. In comparing fuels it is more convenient to make the comparison on the basis of

TABLE 3 AVAILABILITY AND PRICE OF SOME OXIDIZERS

Propellant	Availability	Cost, cents per lb
Nitrogen tetroxide	Potentially good	15 <sup>a</sup>
Mixed acid	Good	4-5
Liquid oxygen	Very good	3-4
Hydrogen peroxide	Fair at present, in concentrated form	63

<sup>a</sup> Price in cylinders. With large production permitting tank car shipments, a price of 5 cents per lb might be visualized.

pounds of thrust obtained per pound of fuel consumed per second. This is known as specific impulse and is calculated according to the following equation (13, 14):

$$I = \frac{w}{g} = 6.92\phi \sqrt{\frac{T_c}{m}} \sqrt{\frac{2k}{k-1} \left[ 1 - \left( \frac{P_e}{P_c} \right) \frac{k-1}{k} \right]}$$

where:

- $I$  =  $w/g$  = specific impulse, lb per lb sec
- $w$  = effective exhaust velocity for rocket, fps
- $g$  = acceleration due to gravity = 32.174 ft per sec<sup>2</sup>
- $\phi$  = velocity coefficient =  $\frac{\text{actual velocity}}{\text{ideal velocity}}$
- $T_c$  = temperature of gases in combustion chamber, R
- $m$  = molecular weight
- $k$  =  $c_p/c_v$  = specific heat ratio
- $c_p$  = specific heat at constant pressure, Btu per lb
- $c_v$  = specific heat at constant volume, Btu per lb
- $P_e$  = absolute pressure of gases at nozzle exit section, psia
- $P_c$  = combustion chamber pressure, psia

Since all terms of this equation are essentially constant with the exception of  $T_c/m$ , it is possible to make specific-impulse generalizations on the basis of this term alone. In other words, the energy content of the combustion products of the adiabatic reaction of an oxidizer with the usual propellant fuel should be high and the products should possess a low mean molecular weight.

Nitrogen tetroxide fulfills these requirements to the extent that its performance exceeds the performance of hydrogen peroxide, red fuming nitric acid, white fuming nitric acid, and mixed acid.

TABLE 4 DENSITY OF SOME FUELS AND OXIDIZERS

Propellant	Density at 20 C
Nitrogen tetroxide	1.45
Mixed acid	1.56
Red fuming nitric acid	1.5-1.55
White fuming nitric acid	1.49-1.50
Liquid oxygen	1.14 (a)
Hydrogen peroxide (87%)	1.39
Hydrogen peroxide (100%)	1.46
Ethyl alcohol	0.789
Methyl alcohol	0.791
Monoethylaniline	0.96
Nitromethane	1.13
Hydrazine	1.01
Hydrazine hydrate	1.03
Gasoline	0.75 (b)

a At boiling point. b Average.

If the high specific impulse were the sole factor governing the selection of rocket fuels, the frequently proposed liquid hydrogen-liquid oxygen system would be satisfactory. The deficiency of this system is in the low density of liquid hydrogen (4.4 lb per cu ft) and the subsequent large size and weight of the storage tanks. Nitrogen tetroxide by contrast has a density of 90.4 lb per cu ft and compares favorably with other oxidants in this respect. See Table 4.

There are many other factors which a rocket engineer must con-

sider in the design of a satisfactory fuel system including spontaneous ignition, catalytic decomposition, heat transfer, heat of combustion, viscosity, vapor pressure, chemical stability, and exhaust velocity (15). A detailed study of each would require a great deal of time but in general nitrogen tetroxide fulfills the requirements imposed by these conditions.

In closing we quote Klein (16):

"A practical propellant must be safe to store and handle, must provide a maximum specific impulse with a minimum volume per unit weight, must be readily available and inasmuch as we are all taxpayers, should be cheap."

Nitrogen tetroxide may serve as one key to the successful synthesis of this ideal rocket propellant.

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# INSTRUCTION AND RESEARCH IN JET PROPULSION

By Luigi Crocco

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Organization of The Daniel and Florence Guggenheim Jet Propulsion Center within the aeronautical-engineering department at Princeton University is discussed. Research facilities are described and several programs of research are enumerated. In the second half of the paper, the author relates pioneer experimental work in Italy beginning in 1927 in which he collaborated. This covers development of solid-propellant rockets, and bipropellant engines; also researches on monopropellants.

DEVELOPMENT in rocket and jet devices is creating a new situation in the field of engineering and research instruction. If, in the past, the design of the engine and the design of the airplane were dependent upon widely separated branches of applied mechanics, today the propelling and the propelled unities are becoming interdependent in their characteristics and achievements, so that contacts between the two different fields appear every day more necessary. But what is more significant is that the branches of applied mechanics upon which the development of the propelling and the propelled unities are based have a tendency to overlap more and more, since in both of them the problems connected with the high-speed flow of gases, with or without viscosity or heat conductivity, are taking a fundamental place.

Another important point with which the development of rocket and jet propulsion is concerned is that, as in other branches of mechanics, the empirical stage of development is already finished. What could be reached without the help of extended analytic research has already, except in a few exceptional cases, been obtained, and today, it is necessary to have more highly qualified people working patiently on the fluid-dynamical, mechanical, chemical, and technological details on which the improvement of propelling systems is based.

## Instructional Requirements and the Guggenheim Centers

The repercussions of this evolution in the instructional field are immediately deduced. If, in the older programs of the aeronautical-engineering schools, the teaching of aerodynamic and structural principles was almost entirely separated from the teaching of thermal and mechanical problems,

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today, it is necessary, especially in the field of propulsion, to mix them more or less completely in a single fundamental plan of instruction in which the basic principles of gas dynamics, combustion, heat transfer, and high-temperature technology must be represented. Subsequent specialization can be achieved in more detailed fields but only after starting from this common basis.

With the purpose of meeting these instructional requirements, the Guggenheim Foundation, with the sensitivity that many times has caused it to give its moral and economic support to scientific and instructional enterprises, is once again the leader in the advancement of scientific studies with its latest decision, to establish two new centers of jet propulsion in Pasadena, Calif., and Princeton, N. J. The purpose of these centers is: (1) To give to a number of graduate students during a fifth year of instruction, a common scientific background in the field of high-speed propulsion; (2) with the institution of postgraduate fellowships, to allow to a selected group during a sixth year, longer and deeper instruction in the particular matters of jet propulsion; and to train them in the following years toward scientific research in this field; and (3) to promote and perform research in the different fields on which the progress of jet and rocket propulsion depends.

### **Program of Instruction**

For the first general purpose the Guggenheim Center at Princeton had to add but little to what had already been in the program of the aeronautical-engineering department for several years. In fact, this program was already directed to give a good basis in high-speed aerodynamics and jet propulsion since it included, together with some courses on more general aeronautical aspects, a course in compressible aerodynamics and one in jet propulsion. To make the program more complete, courses were added on advanced problems of gas dynamics, of combustion and mixing phenomena, and of boundary layer and heat transfer. Courses taken during the fifth year vary somewhat for each student, depending upon his previous general instruction. This is due to the fact that it was thought more profitable for a higher level selection to admit students with a wide range of training and experience. At the end of this fifth year however all jet-propulsion students will have a good basis for thesis work and for a master of science degree.

The second purpose connected with the sixth-year instruction program for the Guggenheim fellows is new for the aeronautical-engineering department at Princeton. It will begin next year and will include courses in mechanical design and testing of jet engines and rockets, on the aerodynamic design of compressors and turbines, on high-temperature materials, and on chemical problems connected with jet propulsion. Moreover, we

think that even if some of the fellows are especially attracted to theoretical research, it will be equally important for them to know as much as possible of the problems of practical operation and experimentation. Therefore, a considerable emphasis will be given to laboratory instruction and to minor personal experimental work on aerothermodynamics and on rocket and jet propulsion. The programs are still in a state of flux and it is believed that only the practical results of the first years will direct them toward the best distribution for which they are designed.

Concerning the laboratory instruction, we have in Princeton excellent experimental facilities for sponsored supersonic, combustion, and rocket research. How far these facilities can be used for instructional purposes is difficult to say now, but we can be sure that there will be some interference between such use and the sponsored research. That is why we are now planning the institution of separate facilities for independent use as instructional devices and as a basis for free experimental research connected not only with the sixth-year program, but especially with the doctorate thesis. Obviously, this laboratory expansion cannot be achieved without a corresponding economic expansion.

### Problems of Research

There is no well-defined separation at Princeton between the center of jet propulsion and the aeronautical-engineering department. For the moment, the program of research of the center cannot be isolated from the one which is already in development in this department except for personal contributions in theoretical research of some members of the staff. Only when the Guggenheim fellows begin their work of research, and provided we can afford the laboratory facilities for free research, will there be a real theoretical and experimental program particular to the center. For the moment, the greatest part of the research of the staff is connected with sponsored research, but as this sponsored research at Princeton is generally in the domain of the basic problems that are of fundamental importance to high-speed flight and jet-propulsion development, and as the inspiration for the personal scientific research of the staff is often afforded by the sponsored research, it may be worth while to make a brief statement of main projects and eventual objectives.

There are in Princeton, two newly developed wind tunnels, designed for operation at high Mach number and widely variable Reynolds number. Both of them are intended to be used for research on the interaction between shock waves and boundary layers on wings, bodies, and ducts. A third supersonic tunnel for extremely high Mach number is in the planning stage, and will be used for experimental research in the hypersonic range.

So far, a certain amount of work has been done in one of the existing

tunnels on the problems of the condensation of the components of the air in high-speed wind-tunnel operation. When air expands in a nozzle with high expansion ratio, the temperature of the air can decrease well below the limit where, statically, the oxygen or the nitrogen should condense in liquid drops. But as the velocity after the expansion is very high, and as a re-compression takes place soon after the expansion, the time during which the air remains at the lowest temperature can be short. Now the problem is whether the available time is sufficient for an appreciable condensation. Some interesting results have already been deduced, but more tests and computations are needed to give the complete answer. This is, then, a refined problem of physical chemistry, but its practical repercussions on the experimental technique make it one of the important questions connected with tests at extremely high Mach numbers.

Another important field of concentration at Princeton is concerned with the problems of the boundary layer. It is well known that the solution of the dynamic equations of gaseous motion is made much easier if one considers the gas as an ideal gas, without viscosity and heat conductivity. In fact, it is shown that this assumption is possible everywhere except in the immediate neighborhood of solid walls, where, in a thin layer called the boundary layer, the effects of the viscosity and heat conductivity are concentrated, and on which all the phenomena connected with friction and heat transfer depend. This is the first reason which makes the study of boundary layers interesting for jet propulsion, since it allows the computation of the frictional drag (which, especially for rockets, can be essential) and of the heating and cooling properties of the fluids, which are so important for the practical developments of rockets and jet engines. The Princeton Center is especially interested in the development of the theory of laminar and turbulent boundary layer and in the study of the practical problems connected with them, such as rocket cooling, temperature of turbine blades, effect of boundary layers on the performances of compressors, and friction heating at high Mach number. Moreover, one problem that has already attracted attention at Princeton is the problem of the stability of laminar boundary layer of gases, with the purpose of finding the dynamic and thermal conditions favorable to stability. This is an interesting problem connected with the reduction of frictional drag on wings and bodies.

Another reason for interest in the boundary layer is that in many cases the boundary conditions for the solution of the dynamic equations of the idealized gas are substantially influenced by the behavior of the boundary layer. This happens, for instance, when separation phenomena are present (such as in diffusers and elbows, and in centrifugal and axial compressors), or when, in supersonic flow, an interaction arises between shock waves and boundary layers. This is a problem which has still many obscure points and which will continue to attract attention, both from a theoretical and from an experimental point of view.

Experimental research on a special type of intermittent ramjet and on ducted rockets has also been going on in Princeton laboratories. The problem of the ducted rocket has some connection with that of thrust augmentors, and both of them seem to have been studied only in limited directions. So far, there is no definite answer to the question whether these devices can result in a useful improvement in jet propulsion.

It is known that some gain in thrust can be obtained by mixing, under a pressure different from the ambient pressure, the exhaust gases from a jet engine with air from the surroundings, and then allowing the mixture to reach again the ambient pressure. There is evidence that the gain could be quite substantial under static conditions, and that it will decrease with the forward speed. Its application to jet devices, whose high fuel consumption at low speed represents an important inconvenience, has been many times suggested but without a definite conclusion.

The case of the rocket is somewhat different, since in many cases the rocket is operated with insufficient quantities of oxygen, so that the exhaust gases can still burn in the air and develop more heat. In this case the additional heat can be used as in the ramjet, to obtain a thrust which is likely to increase with the forward speed, and the gain can be substantial at high velocities. It is in the Princeton programs to find, theoretically and experimentally, a definite solution to the problem whether these added complications to the jet engine and to the simple rocket motor will pay, and in what limits.

There is interest also in a program of research on combustion, both in jets and in rockets. The problems of combustion are complicated if the aim is to analyze them in their complete physicochemical aspect. Chemical knowledge of the processes of combustion is still rough and incomplete, despite the numerous research studies on this subject. Only some of the simplest cases have been satisfactorily explained qualitatively, if not quantitatively, but investigators are still far from even a qualitative explanation of what takes place with ordinary propellants and fuels. In this situation, the only possibility of physical understanding of the phenomena observed in quiescent combustion chambers is based on the consideration of some characteristic quantities like ignition lag, ignition temperature, flame velocity, that can be observed and measured by simple tests without going into their molecular explanation. Obviously, by the substitution of this macroscopic picture of combustion for the real microscopic one, many details are lost and the effects of different physical and chemical conditions on the behavior of the aforesaid characteristic quantities cannot be predicted and have to be deduced from tests. But even when these effects are sufficiently known, the prediction of the behavior and operating limits of a practical combustion chamber is still hazardous because little is known of the fluid-dynamical processes involved. For instance, experience has shown that high rates of heat release for a given volume of com-

bustion chamber can be maintained only through a high rate of turbulence or through concentrated eddies and dead spots, as in flame holders. But no one is able to predict which is the best type of artificial turbulence or of flame holder to obtain a given rate of heat release with the lowest possible losses. Only more careful and detailed research in this field will give the possibility of discriminating the influences of the different quantities involved and obtaining better combustion chambers. A program of research is being planned in the hope that some contribution can be made to the solution of this interesting problem.

The processes of the combustion in rockets are even more obscure. The effects of mixing of propellants, of their spatial distribution, of the evaporation of droplets, are here superimposed upon the real combustion phenomena, and so far, it seems that no satisfactory theory has been worked out. To improve the design of rocket-combustion chambers a clearer understanding of the mechanism of combustion must be reached, and here too, we are planning some basic research.

This short enumeration of programs of research is only to give a general idea of present objectives at Princeton. But, obviously, there are many other problems to be considered in the future, and it is quite hazardous to attempt to crystallize a long-distance program of research in such a wide and fast-moving matter as jet propulsion.

### An Historical Digression

The empirical epoch of the rocket and jet development is finished, and patient and refined work is now necessary to achieve further advances in this field. Many highly specialized persons in many countries have to co-operate to enlarge the frontier of the technical possibilities and to insure to rocket and jet propulsion their natural field of operation, that of extremely high altitudes and velocities. But in this great adventure of the science, we must not forget the people who, in the midst of nearly general incomprehension, started, a few decades ago, the fight for jet propulsion.

It is particularly gratifying that the professorships connected with these centers are called by the name of the American pioneer Goddard, who was one of the first to understand the great future possibilities of rocket flight and to work for their development with the liberal support of the Guggenheim Foundation.

Of the early pioneer work in the different countries, some are widely known; some are still practically unknown. As I was associated with the first work in Italy on the problem of solid-propellant and liquid-propellant rockets, and as little of this work is known except to restricted technical groups, it might be interesting from an historical viewpoint to give here a short summary of the methods employed and of the results obtained.

### Research on Powder Rockets

The experimental work on solid-propellant rockets, sponsored by the Italian General Staff, began in the year 1927 under the direction of Gen. G. A. Crocco, who, since the end of the first world war, had done many theoretical researches on the possibilities of rockets and jet propulsion. I gave my constant personal collaboration to these researches which were conducted with the help of the chemical company, Bombrini Parodi Delfino, and its technical director, Dr. Marenco. The research had a duration of two years and the results, if compared with the expense involved of only a few thousand dollars, were quite substantial, since the rockets that were tested contained most of the fundamental features of present-day rockets.

Our first general tests on powder rockets were performed in the chamber shown in Fig. 1. The powder in *C* was ignited by an auxiliary charge set off by a remote-operated mechanical device *p-m*. The products of combustion went out through a nozzle *F*. The chamber, for safety reasons, was much larger than was necessary. It was free to move axially on rollers and the thrust was entirely discharged on piston *P<sub>3</sub>* and transformed into oil pressure. The pressure in the chamber and the thrust were simultaneously registered on a rotating drum by means of a two-pencil

recording manometer of the kind used for gas engines. Many types and dispositions of powder were tested. The best results were found with tubular charges of a colloidal solventless powder which was used in Italian naval guns, containing approximately 12.5 per cent of nitrogen. Fig. 2 shows some enlarged sections of the chamber. The tubular charge *C* is held in place by a grid *g*, and ignited by a charge *c*, of ballistite and black powder. Some strips of ballistite were placed in the hole of the charge to give a better simultaneous ignition. One interesting result of the test was that to obtain regular ignition, it

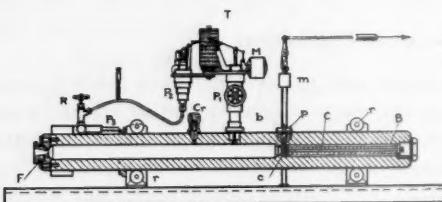


FIG. 1 SCHEMATIC SKETCH OF APPARATUS USED IN 1927 FOR SOLID-PROPELLANT ROCKET RESEARCH

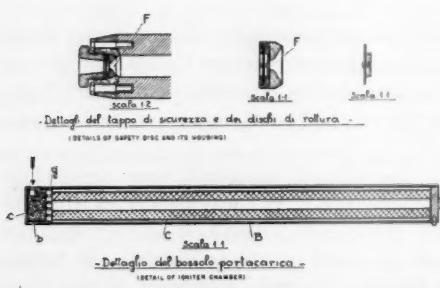


FIG. 2 DETAILS OF COMBUSTION CHAMBER SHOWING SAFETY DISK

was found advantageous to start with the chamber closed. This was accomplished by placing a diaphragm in the exhaust nozzle, as is shown in the details of Fig. 2. As soon as the pressure reached a predetermined value (which in most cases was chosen nearly equal to the pressure of operation) the diaphragm exploded and the constant-volume process was changed into a constant-pressure process. Hundreds of tests were carried out in this apparatus, and with the final arrangements, the results were consistent. In one typical series of runs nearly constant conditions were maintained. The pressure was contained between 50 and 100 atmospheres (750 to 1500 psi), the computations based on the experimental data having shown that the best results were obtained in this range. The measured specific impulse was somewhere between 150 and 170 sec. The difference between different curves of thrust was due to variations in the damping conditions of the thrust-measuring system. Fig. 3 shows a small rocket successfully tested with a small exploding charge *S* and stabilizing tail fins.

The next series of tests was done on greater quantities of powder with the chamber shown in Fig. 4. The volume of the chamber was reduced to its minimum value and the communication between the combustion chamber *C* and the safety space *S* was closed by a strong safety diaphragm *R*. The remaining details of this chamber are about the same as for the first chamber except that the ignition charge was operated at the end opposite the nozzle with a small improvement in regularity. The results of these tests were used for the construction of rockets, one of which is shown in Fig. 5 on its launching ramp. Stabilization was obtained through tail fins. Fig. 6 shows a section of a rocket, which was identical with the one shown in Fig. 5 except for the method of stabilization, which was here obtained by im-

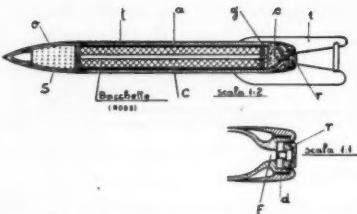


FIG. 3 SKETCH OF SMALL ROCKET WHICH WAS SUCCESSFULLY TESTED

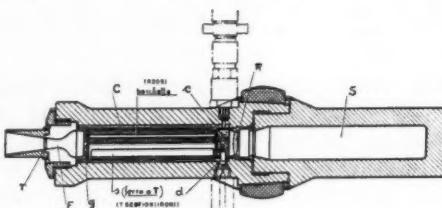


FIG. 4 APPARATUS USED IN THE SECOND SERIES OF TESTS

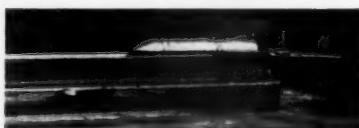


FIG. 5 ROCKET DESIGNED FROM DATA OBTAINED FROM APPARATUS SHOWN IN FIG. 4

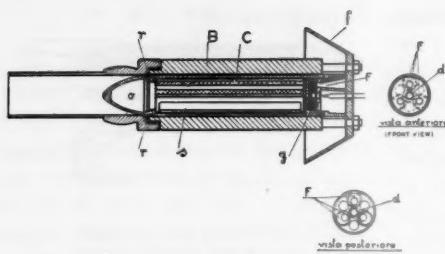


FIG. 6 SKETCH OF ROCKET SIMILAR TO THE ONE IN FIG. 5 EXCEPT FOR METHOD OF STABILIZATION

time, whose gases were exhausted through small tangential nozzles. These rockets were launched with good results and reached velocities of about 1000 fps, which are in agreement with the estimated velocity since the rocket was relatively heavy. The reasons for this high weight were two: First, the concern to achieve safety in the testing of such a new apparatus; second, the fact that in such small rockets the wall thickness was more determined by thermal than by mechanical conditions because of the intense heating from the gases of combustion. In the first rockets launched, the wall reached red heat at the end of the combustion time. To reduce the heating, a thin layer of asbestos was mounted as a protection on the inside surface.

By the end of 1929, the Italian General Staff, judging that the dispersion obtained in our tests was too great if compared with the dispersion of guns, and that the velocity was too small, lost its interest in the powder rockets and the research was suspended.

### Researches on Bipropellant Rocket Engines

In the same year, 1929, some ideas of Gen. G. A. Crocco on the advantages of liquid-fuel rockets were matured and a new research, also sponsored by the General Staff, was initiated in a new direction. The first step was the choice of the propellants. The liquefied gases were excluded for practical reasons. Gasoline was selected as fuel and as oxidizer, after discarding concentrated nitric acid because of the lack of

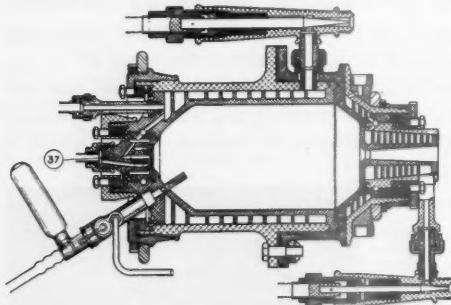


FIG. 7 COMBUSTION CHAMBER USED FOR RESEARCH ON GASOLINE AND NITROGEN DIOXIDE AS ROCKET FUELS

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suitable inoxidizable materials (the stainless steels were still in the initial stage of their development), nitrogen dioxide ( $\text{NO}_2$ ) was selected, which was available at low prices and had good properties. With these two propellants many researches were carried out, first, in the Chemical Institute of the University of Rome with the co-operation of the late Dr. Corrado Landi, then in the Establishment of Constructions of the Italian Air Ministry, with the help of Dr. Riccardo M. Corelli. Fig. 7 shows the section of the latest combustion chamber tested successfully in 1930 which had many of the features of present-day combustion chambers. The chamber was designed so that it could easily be disassembled for inspection and reassembled. The injection of the propellants was through three annular concentric slots, the inner and the outer for the oxidizer, the intermediate for the fuel. The slots (shown in detail 37 of Fig. 7) were designed so as to give three impinging annular jets, thus improving the completeness of mixing. The inner surface of the chamber was protected by a refractory wall of zirconia (oxide of zirconium) not shown in the figure, and the external surface was cooled by the incoming oxidizer. The nozzle was separately and more intensely cooled by the gasoline. It was thought that the preheating and eventually partial vaporization of the propellants could improve the combustion rate. The starting was obtained by first operating the combustion chamber with gaseous hydrogen and oxygen, which were ignited by a torch shown in the figure, and then, after retracting the torch, by increasing the amount of gases so that a definite pressure was obtained in the chamber. It was then possible to achieve the transition to the liquid fuel without any difficulty.

This combustion chamber was operated quite satisfactorily at 10 atmospheres of pressure (140 psi) for durations up to 10 min. The results of the measurements were in good agreement with the computed values.

By the end of 1930, the available funds were exhausted, and despite the promising results obtained, the General Staff did not renew its contract.

### Researches on Monopropellants

In 1932 the work was resumed in a different direction, under the sponsorship of the Aviation Ministry, still under the supervision of Gen. G. A. Crocco and with the co-operation of Dr. R. M. Corelli. This time the purpose was the study of simpler ways of producing high-temperature gases with single liquids. The applications of these monopropellants were seen not only in the field of rocket propulsion, but also in other fields such as torpedo and submarine propulsion, and generally for the operation of engines without air. The fundamental basis, was at the beginning, the idea of stabilizing some liquid explosive, such as dinitroglycerin or trinitroglycerin, with the addition of an organic solvent. It was assumed that if the heat content of the mixture was sufficiently high, the tempera-

Scalpa 1.4

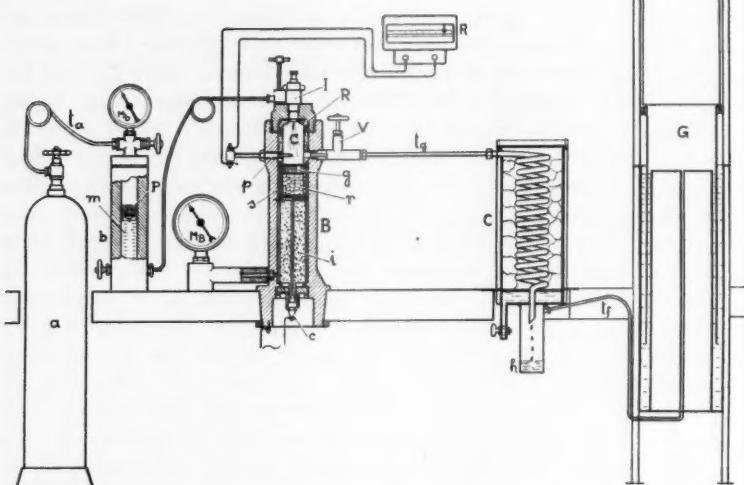


FIG. 8 SKETCH OF APPARATUS DESIGNED IN 1933 FOR STUDY ON DECOMPOSITION OF NITROMETHANE

ture of the products of decomposition would be sufficient to break all the less simple molecules so that the gas resulting from the decomposition would contain only the ordinary combustion gases. Good practical results were obtained, for instance, with a mixture of 70 per cent of trinitro-glycerin and 30 per cent of methyl alcohol. With this mixture we could operate safely small combustion chambers. The analysis of the results showed that the decomposition was complete as in the assumptions, and it developed not more than 1100 Btu per lb despite the small percentage of methyl alcohol. In 1933, with the purpose of finding better solvents than this one, we went through a list of possible organic compounds. In studying the theoretical decomposition and the thermal balance of each compound, I was surprised to find that one of them, the nitromethane, gave results much in excess of the others. I was then induced to perform the same computations on the nitromethane alone, and found that this compound is by itself an excellent monopropellant with extremely good features both for handling and operation. From that time, our experimental research was concentrated upon nitromethane. We studied its stability with respect to shocks and temperature with methods similar to those used later in this country, and with analogous results. We developed many researches on its decomposition with the apparatus shown in Fig. 8. The nitromethane in reservoir *b* was pushed by gas pressure from the bottle *a*, through the injector *I*, into the combustion chamber

C, which contained in the bottom some pieces of refractory material in a refractory container. This container was electrically heated before the test so as to obtain the initial decomposition of nitromethane, and remained at high temperature during the rest of the test because of the heat released by the decomposition. The gases developed were cooled in a cooler, where the condensable products separated, and then collected, in a gasometer for measuring and analytic purposes.

### Results Encouraged Further Research

The results of these tests encouraged some further developments. As the officials were not interested in the rocket work, an application was designed for the operation of torpedo engines in which the nitromethane could give good results, but the Whitehead Torpedo Factory in Fiume, to which the design was submitted, discarded the idea because the nitromethane was much more expensive than the conventional compressed air. Another use was found in the operation of a stratospheric piston engine, that is, an engine which could operate without air. With the economic support of the Air Ministry, a single cylinder was designed and constructed, in which the nitromethane was intended to be injected under high pressure in the hot gases of the previous cycle. The injection was done by means of a Diesel pump, but the lack of positive lubrication in this pump and the high-temperature spots on the piston when, after some minutes of operation, the lubricating oil film was removed, were the causes of an explosion in which the testing apparatus was damaged and Dr. Corelli and I were injured. As a consequence, the work on nitromethane was suspended in 1935.

In conclusion, I will add that in 1946 I had the opportunity of resuming, in France, the research on the use of nitromethane in rocket engines. This research, performed as a contract for the French Army, has confirmed the interesting results obtainable with this propellant.

### Conclusion

The result of the great amount of effort developed in connection with jet and rocket propulsion will, in the near future, open to mankind the domain of the high velocities of flight. Some people are dubious about the utility of this new conquest. I am not. If we look back to the mechanical progress of this century, we recognize that aviation has been one of the fundamental factors in making the world smaller. We can induce therefore that the advent of higher velocities will knit the continents still closer together. This changing in the dimensions of the world has not only useful material repercussions; I do believe that it shall have most important moral consequences in giving to men the feeling of their brotherhood and of the necessity for peace.

## American Rocket Society News

### Upper-Atmosphere Research Discussed at New York Section Meeting

ONE of the major peaceful applications of jet propulsion—that of upper-atmosphere research—is currently being retarded because of the lack of a light, simple, reliable rocket capable of carrying a small pay load to moderate altitudes and one which could be transported and fired by small research crews in many parts of the world.

This point was made by James A. Van Allen, of the Applied Physics Laboratory, The Johns Hopkins University, Baltimore, Md., before a meeting of the ARS New York Section, March 17, 1950. Dr. Van Allen's subject was "The Use of Rockets in Upper-Atmosphere Research."

Dr. Van Allen is an engaging speaker and his lucid exposition of the geophysics of the upper atmosphere and what his organization was doing to expand knowledge in this field won an appreciative response from more than 200 members and guests who attended.

#### Spectacular Film Shown

His talk was concluded with a 15-minute color film showing rocket firings at White Sands Proving Ground and on board the U.S.S. *Norton Sound*. In a breath-taking conclusion the film took the viewers on a rocket ride to an altitude of 70 miles as seen through the lens of a camera installed in one of the White Sands rockets. The film showed the desert and mountain ranges receding until the earth appeared as a vast backdrop. At the end of the powered flight when the rocket began to gyrate and tumble, the earth and sky flashed alternately on the screen revealing the curved horizon and recognizable stretches of the Pacific Coast some 700 miles away.

According to Dr. Van Allen, rocket-firing techniques and attitudes of research workers have changed much since the work began in 1946. The scientists are no longer

"altitude happy" but have matured to the extent that much of the original excitement over spectacular altitudes and spectacular take-offs and flights has given way to sounder thinking about the proper role of rockets in the much broader field of upper-atmosphere research, and on the reliability of results obtained from firings.

At the present time improvement of research techniques has overtaken the engineering art of rocketry. What was needed most, Dr. Van Allen stated, was an abundance of inexpensive reliable rockets to enable research groups using different techniques to expand and verify upper-atmosphere data collected from sites in other parts of the world. A sound science, he continued, must be founded on data that have been checked by repeated soundings and by different techniques.

#### New Knowledge Available

Before the advent of the rocket, high-altitude research, Dr. Van Allen said, was limited to about 100,000 feet reached by balloons carrying small pay loads. Rockets enabled investigators to surmount the atmosphere and already much new knowledge has been obtained. For example, distribution of temperature, therefore, pressure density, of the atmosphere has been explored to about 70 miles. In the field of solar spectroscopy, an entirely new region of the solar spectrum below 2900 Å. has been recorded and subjected to identification of Fraunhofer lines and intensity study. Altitude distribution of ozone has been measured with the result that it is now known that the abundance of ozone above 30 miles is negligible. Samples of the atmosphere at 45 miles showed that contrary to common impression, no separation of the light gases in the air occurs in the upper atmosphere. The earth's geomagnetic field has been measured up to 70 miles.

Most of the data obtained, however, have been limited to the region around White Sands, N. Mex. Future research calls for soundings elsewhere. Dr. Van Allen reported that pioneer attempts to collect data at the geomagnetic equator have already been made by the Applied Physics Laboratory on the U.S.S. *Norton Sound*.

#### New York Section Officers

At the regular Board meeting of the New York Section of the American Rocket Society the following officers were appointed for 1950: President, James Wheeler, Sperry Gyroscope Company; vice-president, James Nutt, Jr., Reaction Motors, Inc.; secretary, Thomas Gardner, Hoffman-LaRoche; and treasurer, P. Winteritz, Reaction Motors, Inc.

#### New Mexico-West Texas Section

THE election of officers for the New Mexico-West Texas Section resulted in the following men being elected for the year 1950: President, H. Karsh; vice-president, E. T. Munnell, for the White Sands Proving Ground area; vice-president, K. K. McDaniel for the Alamogordo area; secretary, John B. Cray; treasurer, John R. Youngquist.

The increase in membership in the New Mexico-West Texas Section in the last two months has been particularly gratifying.

#### Southern California Section

AT ITS last meeting the American Rocket Society Southern California Section elected the following officers: President, C. C. Ross, Aerojet Engineering Corporation; vice-president, N. C. Reuel, North American Aviation, Inc.; secretary-treasurer, R. B. Canright, Jet Propulsion Laboratory, California Institute of Technology.

Mr. Ross addressed a letter to the membership of the Section expressing confidence in the continued growth of the Sec-

tion and announcing that several exceptionally interesting meetings have been planned.

The February meeting of the Section was held in the Arms Laboratory, California Institute of Technology, and was addressed by G. P. Sutton, supervisor, Propulsion Development, North American Aviation, Inc., and H. S. Seifert, chief, Applied Physics Division, Jet Propulsion Laboratory, California Institute of Technology. The meeting was well attended and was enjoyed by all.

The increase in membership in the Southern California Section is very gratifying.

#### New ARS Section Formed

THE American Rocket Society takes pleasure in announcing the establishment of its fifth section. The first meeting of a student section at Purdue University, West Lafayette, Ind., took place on Feb. 22, 1950, when 250 enthusiasts met to elect temporary officers for the newly formed Purdue University Section of the American Rocket Society. The following men will handle the organizational problems until permanent officers are elected: President, Clair M. Beighley; secretary, Eldon L. Knuth; treasurer, Donald L. Dynes. Dr. M. J. Zucrow, long a member of the American Rocket Society, discussed the history of rockets and the ARS, and agreed to assist in the formation of the Section.

The Purdue University Section plans to have lecturers, plant trips, and movies at regular meetings.

The enthusiasm with which the formation of the Section was greeted is an indication of the rapid growth to be expected from this Section, and the National Board of Directors heartily welcomes the group to the American Rocket Society.

#### New Affiliate Corporate Member for ARS

LOUIS M. Barish & Company, New York, N. Y., manufacturers of pumping machinery, have been accepted as affiliate

corporate members of the American Rocket Society.

Louis M. Barish has accepted personally the associate membership which is included with the affiliate corporate membership, and the first advertisement for the Company appears in this issue.

### ARS Session at ASME Spring Meeting

THE American Rocket Society will present a technical session at the Spring Meeting of The American Society of Mechanical Engineers to be held April 12-14, 1950, at the Hotel Statler, Washington, D. C.

Harry Horne, Jr., assistant to executive vice-president and general manager, Reaction Motors, Inc., Rockaway, N. J., will present a paper on "A Discussion of Some of the Problems Facing the Rocket Industry in Connection with Military Planning."

A paper by a member of the Army Ordnance Department will also be presented, the title of which is unknown at press time.

The American Rocket Society session will be held at 9 a.m. on Wednesday, April 12.

The ARS will cosponsor another session with the Gas Turbine Power Division and the Aviation Division of the ASME on Thursday, April 13, at 9 a.m. Speakers at this session will include Carl C. Sorgen, Bureau of Aeronautics, whose paper will be "The Application of Gas Turbine Engines to Naval Aircraft," and O. E. Rodgers, Westinghouse Electric Corporation, who will discuss "Improving Turbojet Performance by the Use of a Variable Area Exhaust Nozzle."

### ARS Member Awarded Patent

EDWARD P. CHANDLER, long a member of the American Rocket Society and now serving on its Board of Directors, was awarded a rocket-projectile

patent on March 7, 1950. The patent covers the adoption of rocket ammunition to various ordnance applications, including automatic arms. The new type rocket may be handled in substantially the same manner as regular "fixed ammunition." Upon firing, the projectile is driven from the gun at high velocity by the instantaneous release of a small volume of gas at a high initial pressure; subsequently, at a safe distance beyond the gun muzzle the propellant-rocket charge becomes effective to continue the flight of the projectile and to accelerate its velocity of translation. Launching is effected without flash or smoke and without substantial recoil. Mr. Chandler's invention affords the means for greatly increasing the fire power of the individual combatants, paratroopers, etc. It permits the firing of rocket ordnance from a closed turret and in positions where the usual rocket blast is hazardous.

### ARS Treasurer Addresses ACS Meeting

G. EDWARD PENDRAY, treasurer and one of the charter members of the American Rocket Society, addressed the Virginia Section of the American Chemical Society on March 10, 1950, at Hopewell, Va.

Dr. Pendray was introduced to an audience of over 300 persons by E. D. Crittenden, chief of research, Solvay Process Division, Allied Chemical and Dye Corporation. Dr. Pendray's talk on "The History and Development of Rockets and Jet Propulsion" included an historical review of the workings of the American Rocket Society and a description of the work of the newly founded Daniel and Florence Guggenheim Jet Propulsion Centers at Princeton University and California Institute of Technology. His talk was particularly interesting and the audience expressed sincere appreciation.

### Membership Roster to Be Published

THE American Rocket Society is preparing a new roster of members which

should soon be ready for distribution.

Each member of the Society has received a postcard form requesting the latest information on addresses and business connections. The secretary will appreciate prompt return of these cards. Every effort will be made to have the roster complete and accurate. Your co-operation will be appreciated.

### ARS Junior Award

**T**HE distinction of receiving an American Rocket Society Junior Award carries with it a recognition of meritorious achievement early in one's professional career. Papers are now being accepted at the New York Office for consideration for the 1950 Award. The award and medal will be presented at the Annual Convention to be held in December. To be considered, papers should be submitted not later than Oct. 31, 1950.

The winning paper will be judged mainly on the basis of content which should reflect original thought and effort. The age of authors of papers is limited to twenty-five. Papers should be on standard size paper, typewritten, and clearly marked: Submitted for Junior Award Competition. Send papers to: Secretary, American Rocket Society, 29 West 39th Street, New York 18, N. Y.

### Dr. Alexander Klemin Dies

**D**R. ALEXANDER KLEMIN, a member of the American Rocket Society since 1935, died at his home in Greenwich Conn., March 13, 1950.

Dr. Klemin's interest in the early developments of the American Rocket Society did much to encourage the work of the pioneers in rocketry. His passing is a severe loss to the aviation field and particularly to the American Rocket Society.

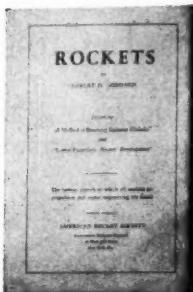
Dr. Klemin, who was technical editor of *Aero Digest* at his death, was head of the Guggenheim School of Aeronautics at New York University from its founding in 1925 until his retirement in 1941. Last January New York University conferred upon him the honorary degree of doctor of engi-

neering for his contributions to aeronautical education.

A native of London, Dr. Klemin received the degree of bachelor of science from the London University in 1907. Coming to this country, he received a year later the degree of master of science from the Massachusetts Institute of Technology, Cambridge, Mass.

Dr. Klemin became a naturalized citizen in 1917, taught at MIT, and did research work for the Army Air Service during the first World War. Before joining the faculty of NYU in 1923, he had been in the field of construction engineering for four years.

In addition to being a member of the American Rocket Society, Dr. Klemin was a member of The American Society of Mechanical Engineers, Society of Automotive Engineers, The Royal Aeronautical Society, the Institute of Aeronautical Sciences, and Engineers and Wings. He was the author of "Textbook of Aeronautical Engineering," "If You Want to Fly," "Simplified Aerodynamics," and "Airplane Stress Analysis."



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